# Evaluation of Grid Modification Methods for On- and Off-Track Sonic Boom Analysis

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# Outline

- Goal
- Introduction
- CFD Codes Used
- Grid Modification Methods
  - Stretched and Sheared Grid (SSGRID)
  - Stretched and Sheared Grid – Modified (SSG)
  - Mach Cone Aligned Prism (MCAP) Method
  - Boom Grid (BG)
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- Concluding Remarks

# Goal

Develop a grid modification methodology to allow accurate and efficient prediction of low boom signatures of supersonic aircraft for both on- and off-track conditions using unstructured-grid CFD

# Introduction

- There has been a revival of interest in supersonic business jets as evidenced by the efforts at companies like Gulfstream, Aerion etc.
- The main issue still remains to be the reduction of sonic boom over-pressure on the ground to a level that would allow supersonic flight over land
- Grid refinement/alignment methods play a critical role in the prediction of boom signatures
  - Stand-alone grid for boom predictions
  - Initial grid for adjoint-based grid adaptation using flow solvers like FUN3D

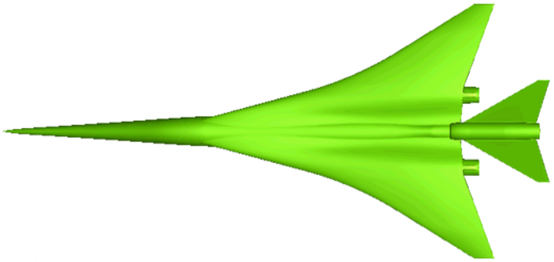
# Introduction

- Grid modification methods have been under development at NASA to enable better predictions of low boom pressure signatures from supersonic aircraft for some time:
  - Stretched and Sheared Grid (SSGRID) – Campbell (2007)
  - Stretched and Sheared Grid – Modified (SSG) – Campbell (2011)
  - Mach Cone Aligned Prism (MCAP) Method – Cliff, Thomas (2011)
  - Boom Grid (BG) – Campbell (2012)

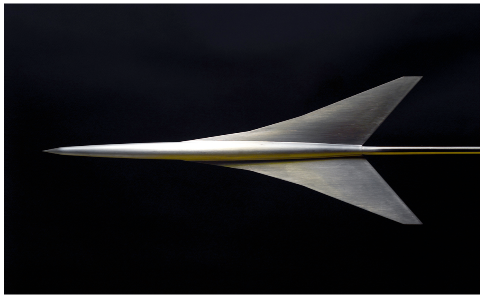
# Introduction

- These four methods are presented here and their predictions have been compared with the experimental results
- Three aircraft wind tunnel models have been studied:
  - Gulfstream Model

  - Lockheed Martin Model



  - Straight Line Segmented Leading Edge (SLSLE) Model



# CFD Codes Used

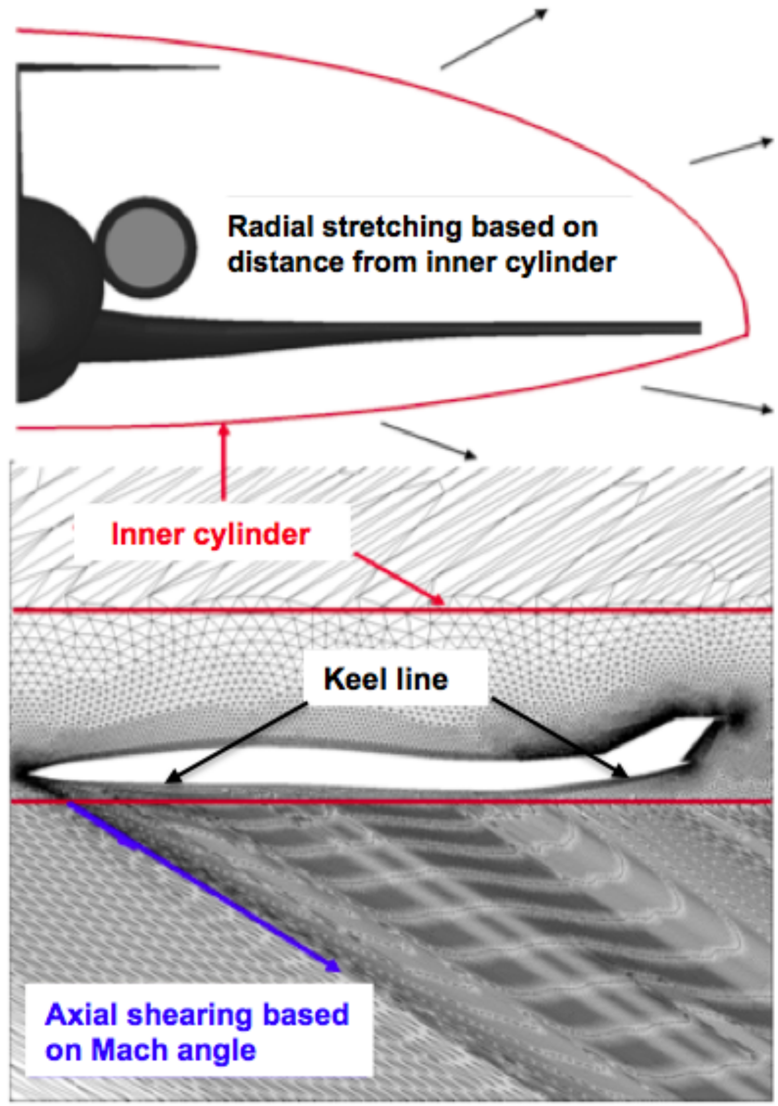
- Tetrahedral Unstructured Software System (TetrUSS) – developed at NASA Langley Research Center:
  - GridTool
  - Vgrid
  - Postgrid
  - USM3D
- AUTOSRC – provides an automated, knowledge-based approach to the placement and sizing of the line and cylindrical sources used in Vgrid

# Grid Modification Methods

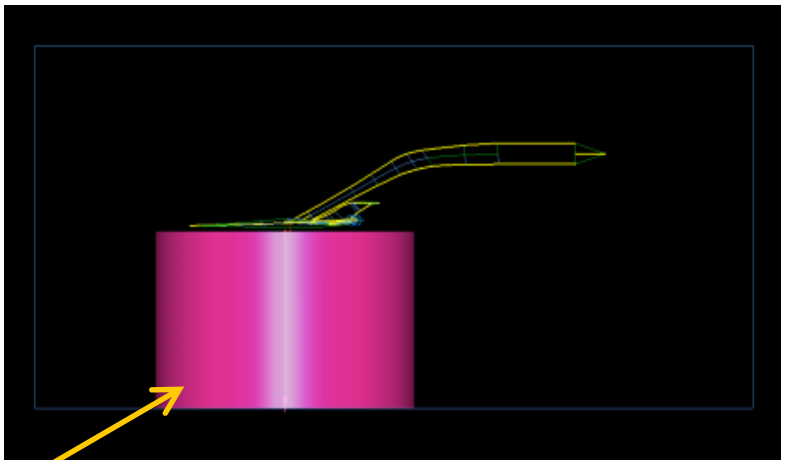
# Stretched and Sheared Grid (SSGRID)

# Grid Stretching and Shearing Controlled by an Inner Cylinder - SSGRID

- The keel line, primary inner cylinder radius, and variable radius are all automatically determined in SSGRID

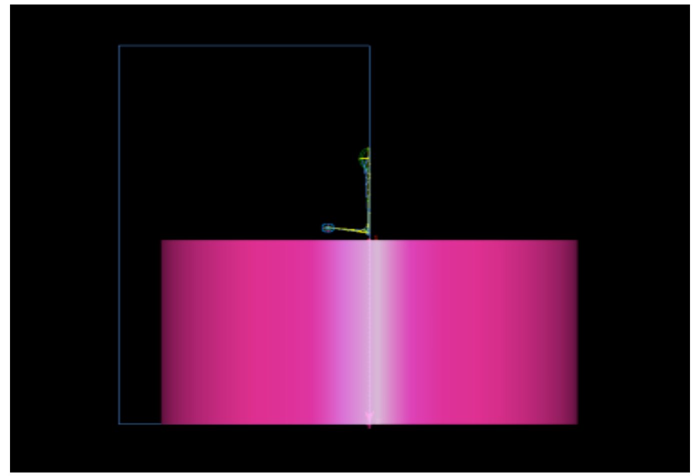


# Grid Generation for the SSGRID Method – Gulfstream Configuration

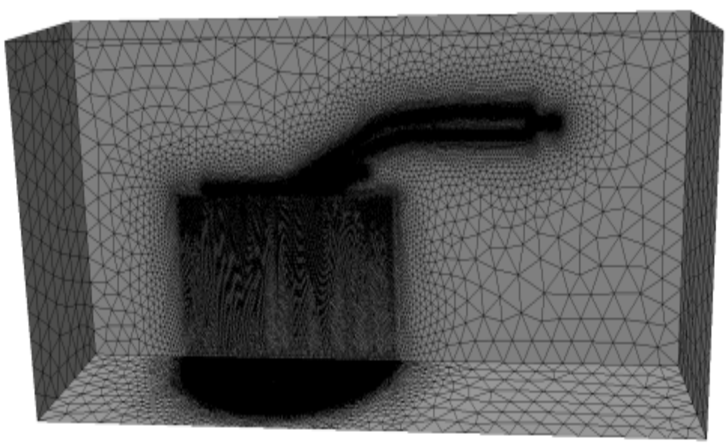


Cylindrical volume source

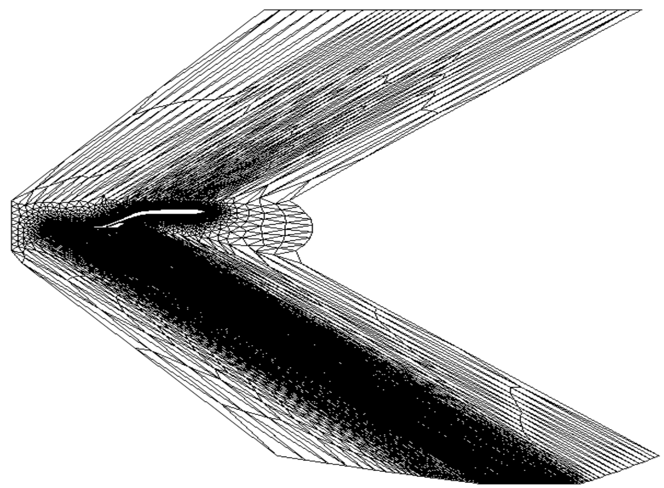
Side view



Rear view



Surface grid



Stretched grid

# SSGRID

Advantages:

- Provides fairly good results at both on- and off-track angles

Disadvantages:

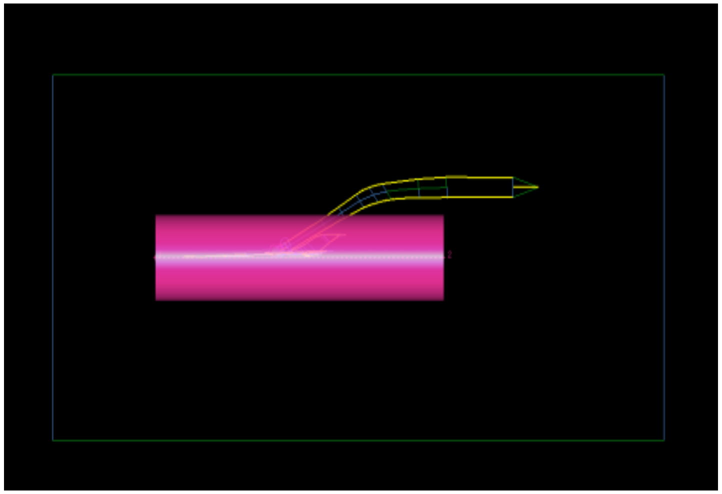
- Grid stretching and shearing generally produce some negative volume cells, so the grid is run through the ADV (ADaptation for Volume grid) code to repair these cells
- ADV negative cell clean up method sometimes fails (certain configurations or extent of stretching)

# Stretched and Sheared Grid - Modified (SSG)

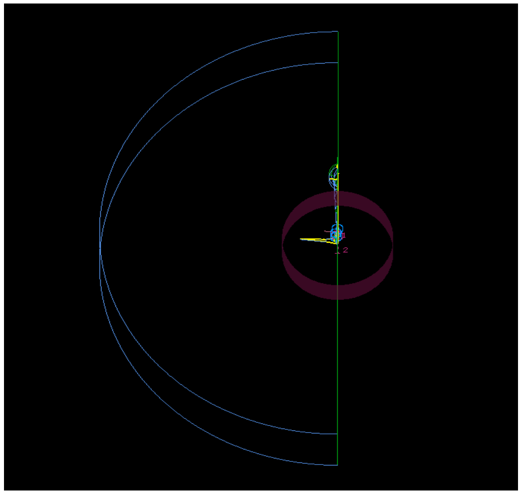
# SSG

- Stretched and Sheared Grid – Modified (SSG) method was developed to address the limitations of the SSGRID code
- Does the shearing and stretching only in the vertical direction and only below the configuration
- Allows the origin of the stretching to be extended above the fuselage centerline - can better propagate flow features emanating from the empennage or engine components

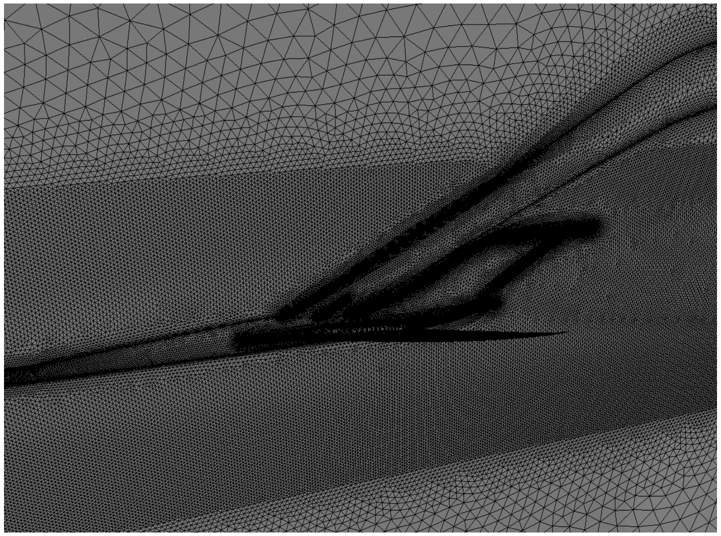
# Grid Generation for the SSG Method – Gulfstream Configuration



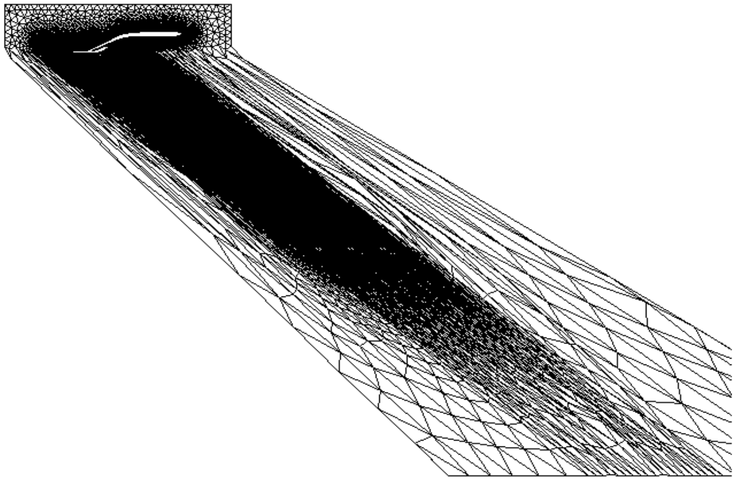
Side view



Rear view



Surface grid



Stretched grid

# SSG

## Advantages:

- Creates fewer negative volume grid cells, while maintaining good on-track boom signature quality

## Disadvantages:

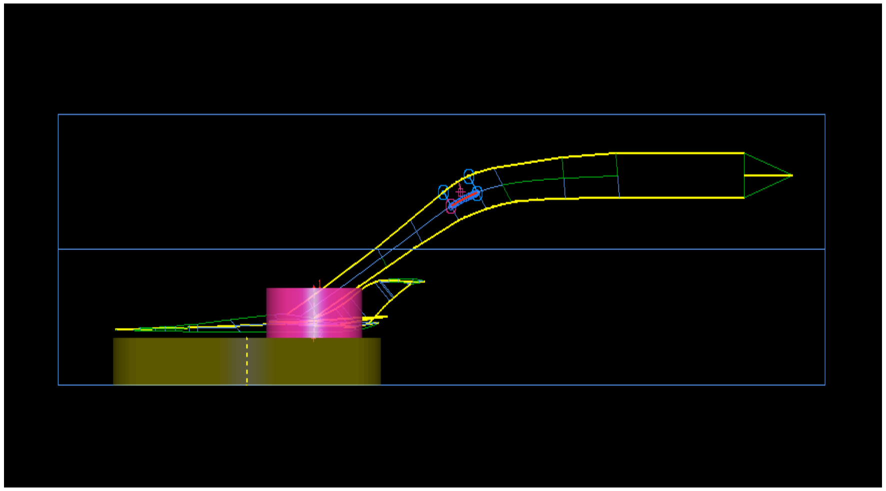
- Initially provided a limited (~ 15 degree) off-track signature capability
- To increase its capability to higher off-track angles, a span-wise component was added to the shearing, with the stream-wise component adjusted to approximate a conical distribution from the keel line
- Negative cell clean up with ADV can still fail (though typically at more distant signature locations than with SSGRID)

# Mach Cone Aligned Prism (MCAP) Method

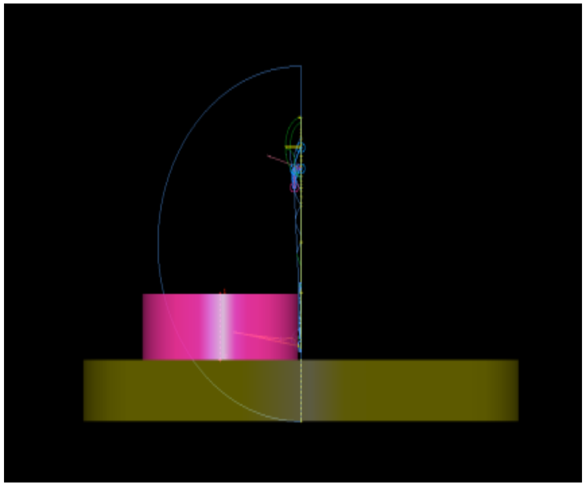
# MCAP

- Occasional grid clean up problem prompted a search for a more robust approach to sonic boom grid generation
- An alternative approach that grew out of the shear/stretch philosophy is the MCAP method. This method applies the shearing and stretching principles to a “collar” grid that is added to an internal “core” grid.
- The collar grid is generated by extruding prisms from the triangulated outer boundary faces of the core grid, with the prism edges being sheared and stretched radially along Mach angles

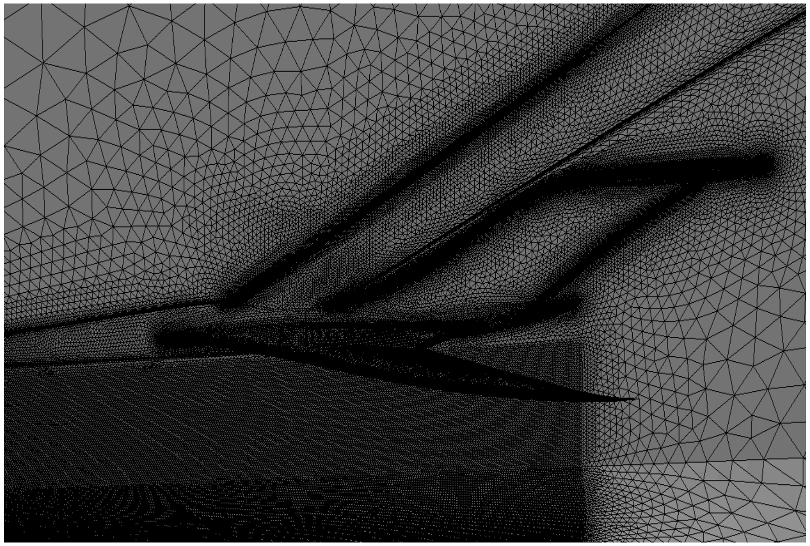
# Grid Generation for the MCAP Method – Gulfstream Configuration



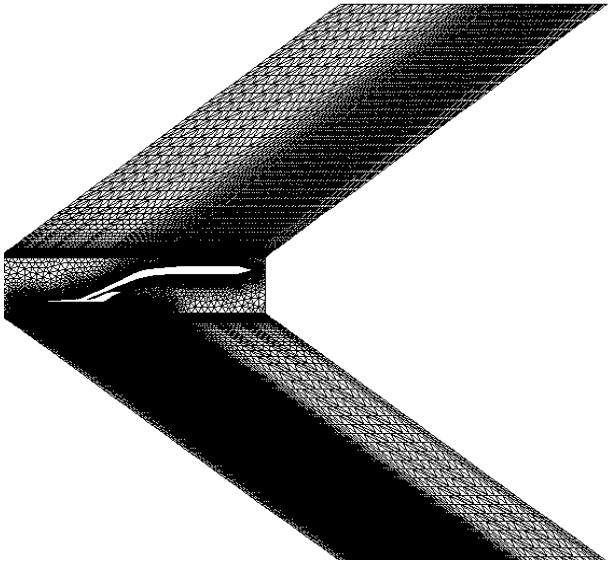
Side view



Rear view



Surface grid



Stretched grid

# MCAP

Advantages:

- Because new cells are being added, the MCAP grids are larger than SSG grids, but the grid quality and flow-solver convergence are greatly improved

Disadvantages:

- With MCAP, the grid generation process requires about an order of magnitude more time than the SSG process
- Grid generation process was relatively slow due to:

  - Conversion of VGRID format files to ‘AIRPLANE’ format and back

  - Procedure for splitting extruded prisms into tetrahedra does not guarantee alignment of matching faces for adjacent cells

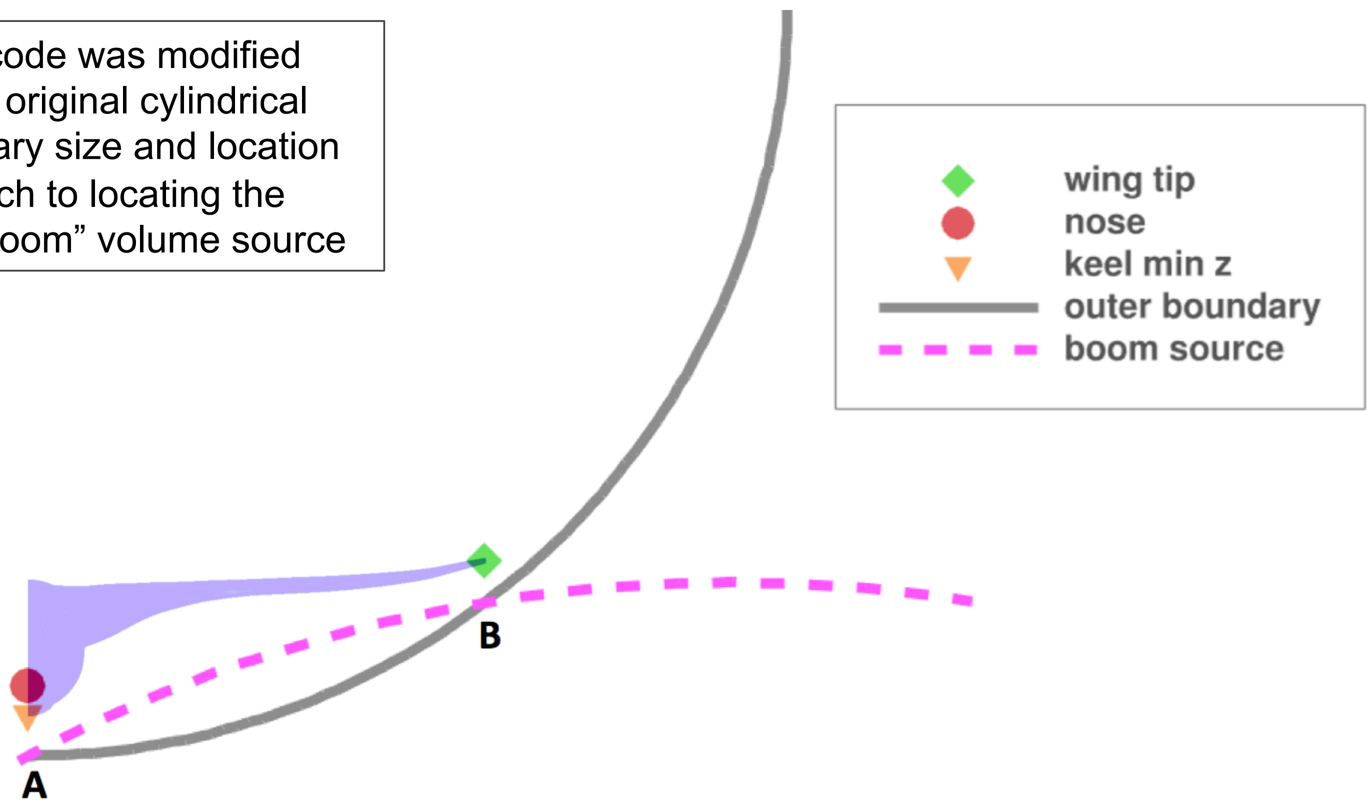
# Boom Grid (BG) Method

# BG Method

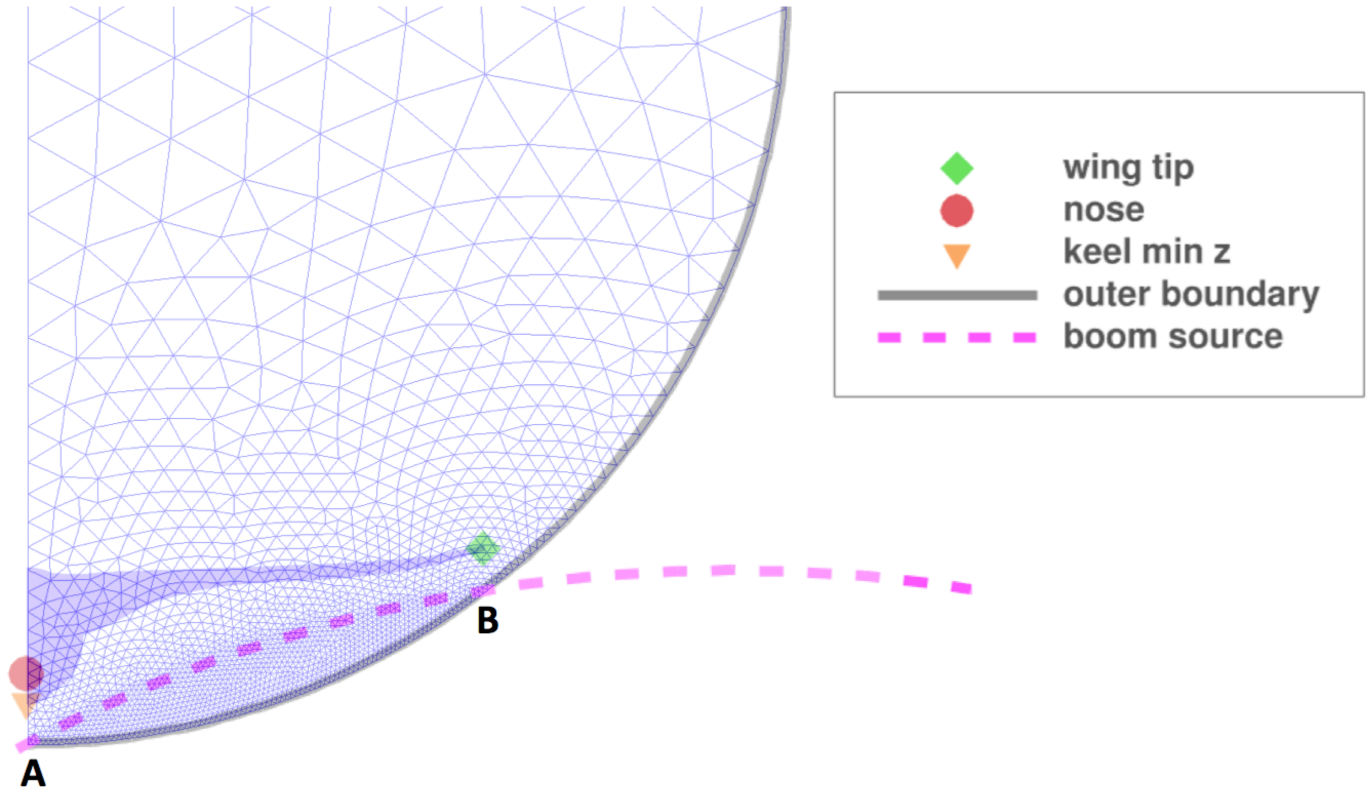
- To alleviate the drawbacks of the previous methods, the BG method was developed in which:
  - Negative volume cells are cleaned up automatically during the grid generation process
  - Grid can be stretched to larger distances (10+ body lengths)
  - Addition of collar grid and stretching is extremely fast (less than a minute)
  - Option for grid clustering at user specified off-track angle
  - Good flow solution convergence has been observed

# Location of the Cylindrical Volume Source

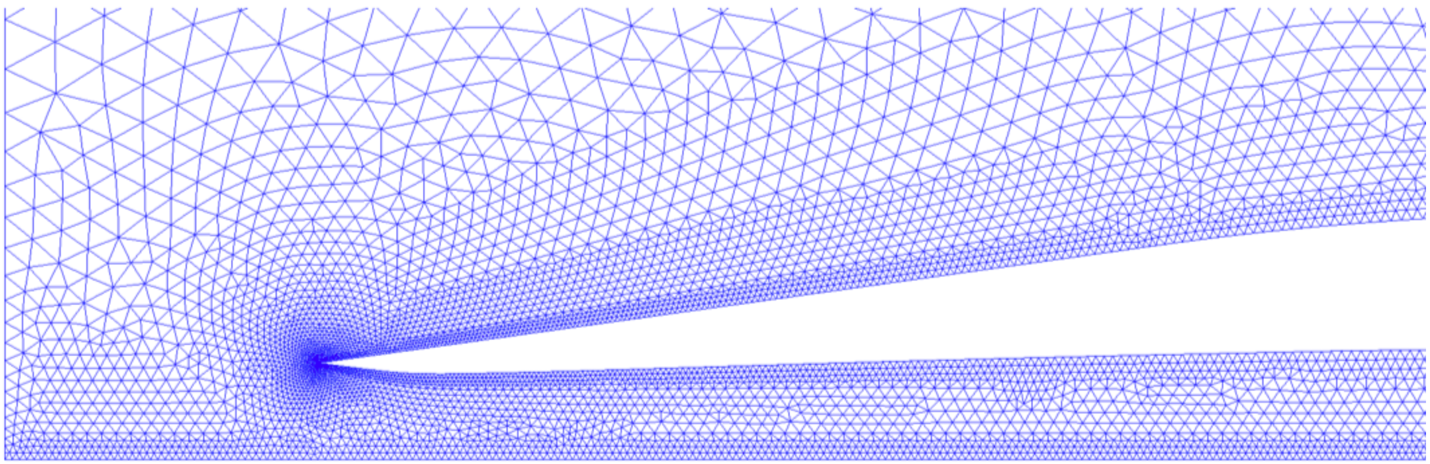
- AUTOSRC code was modified to adjust the original cylindrical outer boundary size and location
- New approach to locating the cylindrical “boom” volume source



# Core Grid Inflow Plane

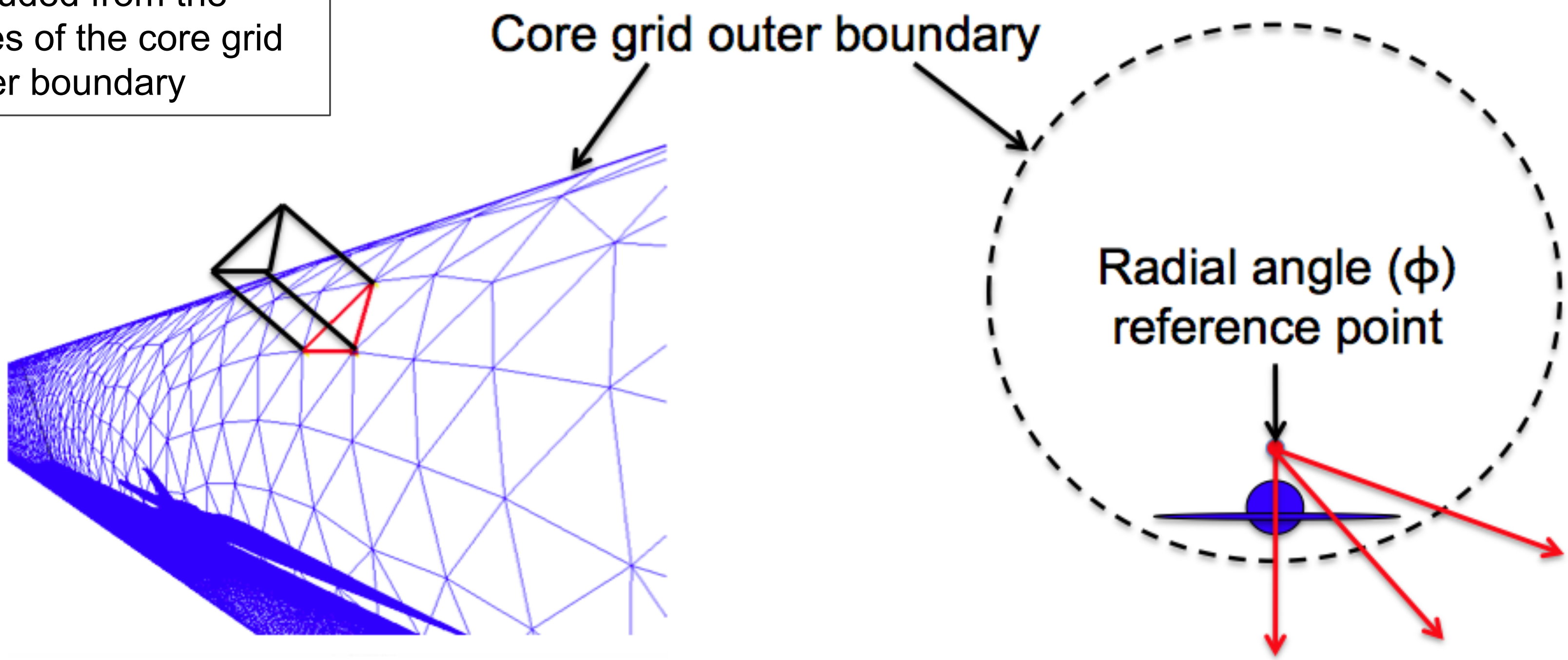


# Symmetry Plane in the Nose Region

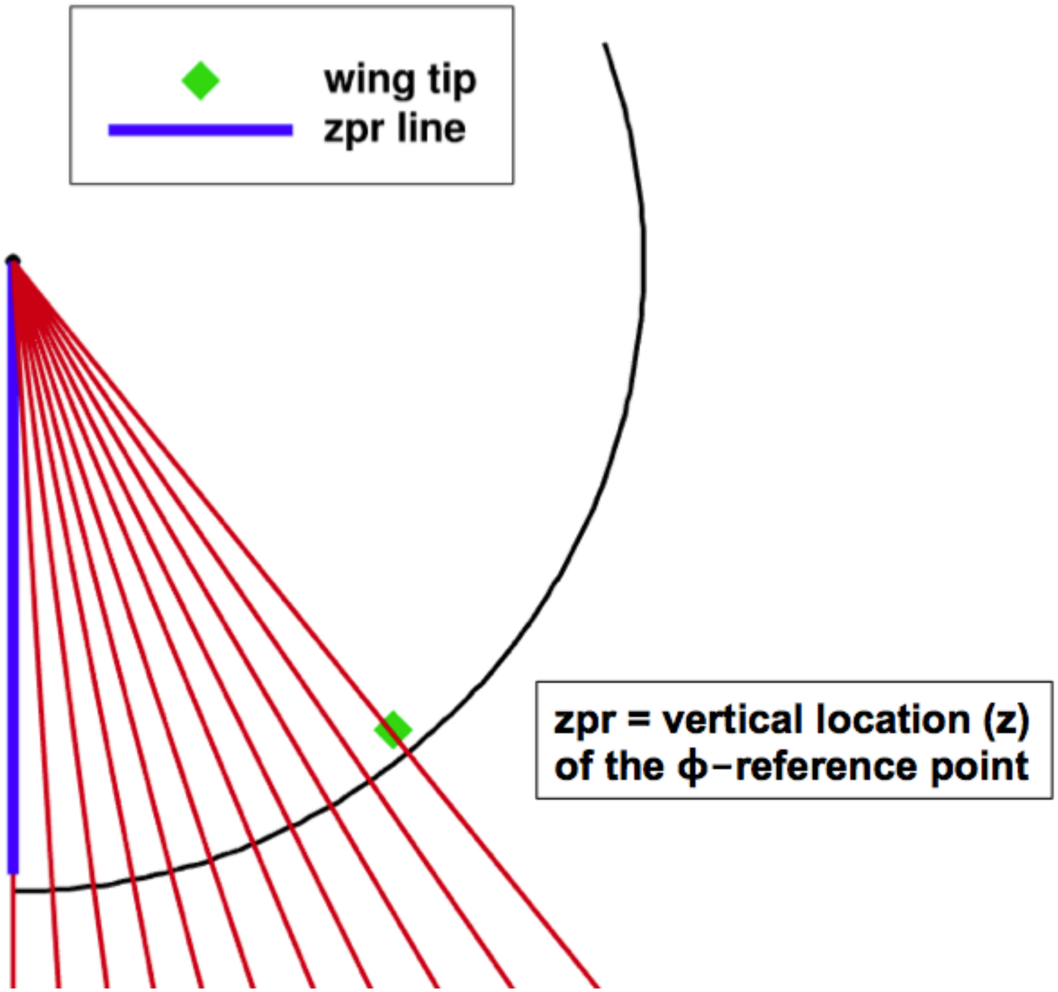


# Prism Extrusion Process in the BG Grid Methodology

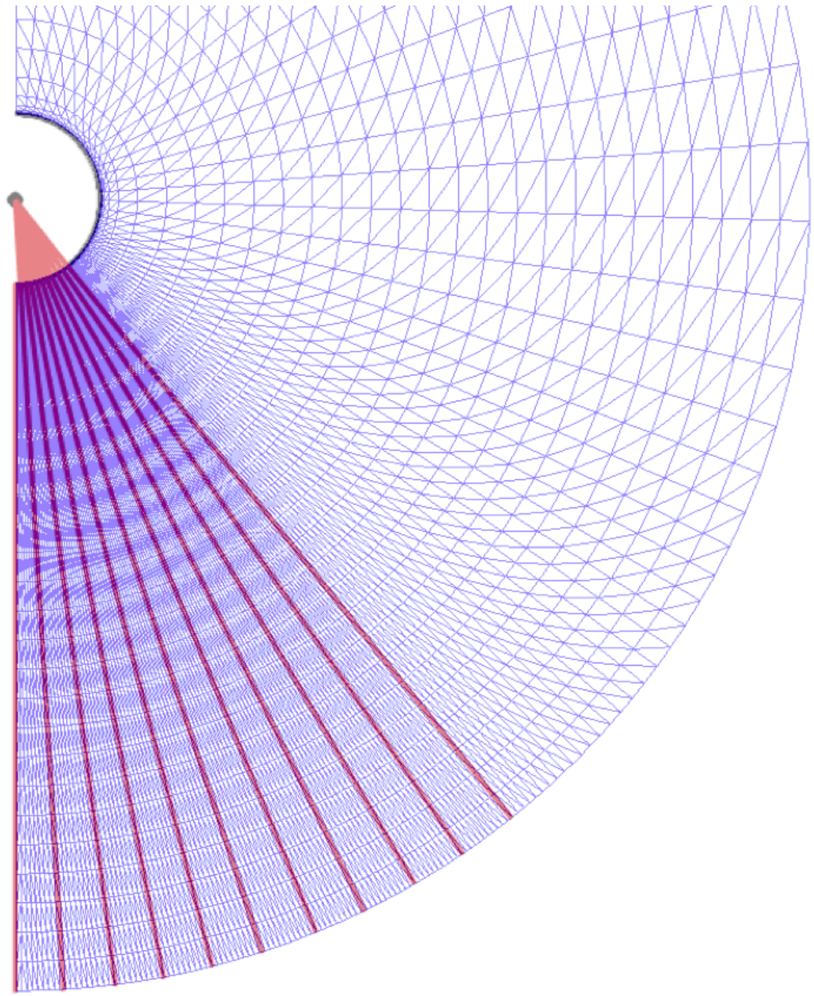
- BG code utilizes the same methodology as Q2D for creating and splitting the prisms
- The prisms are extruded from the faces of the core grid outer boundary



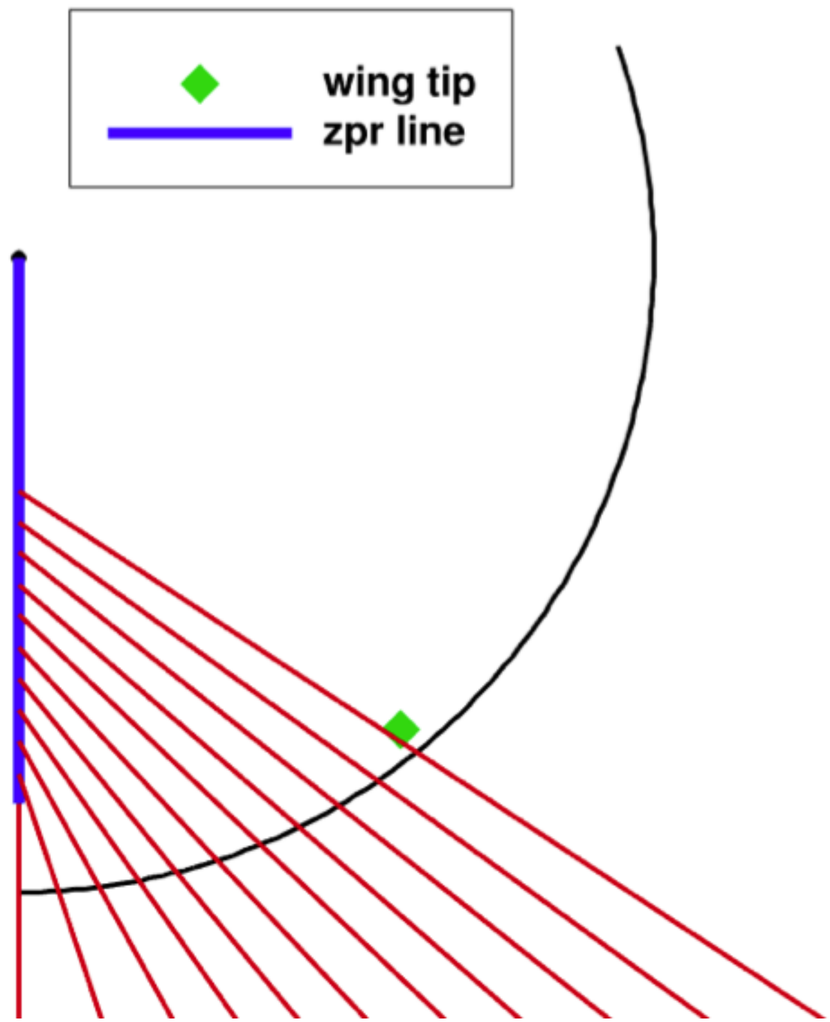
# Zpr Line for the On-Track Signature Case



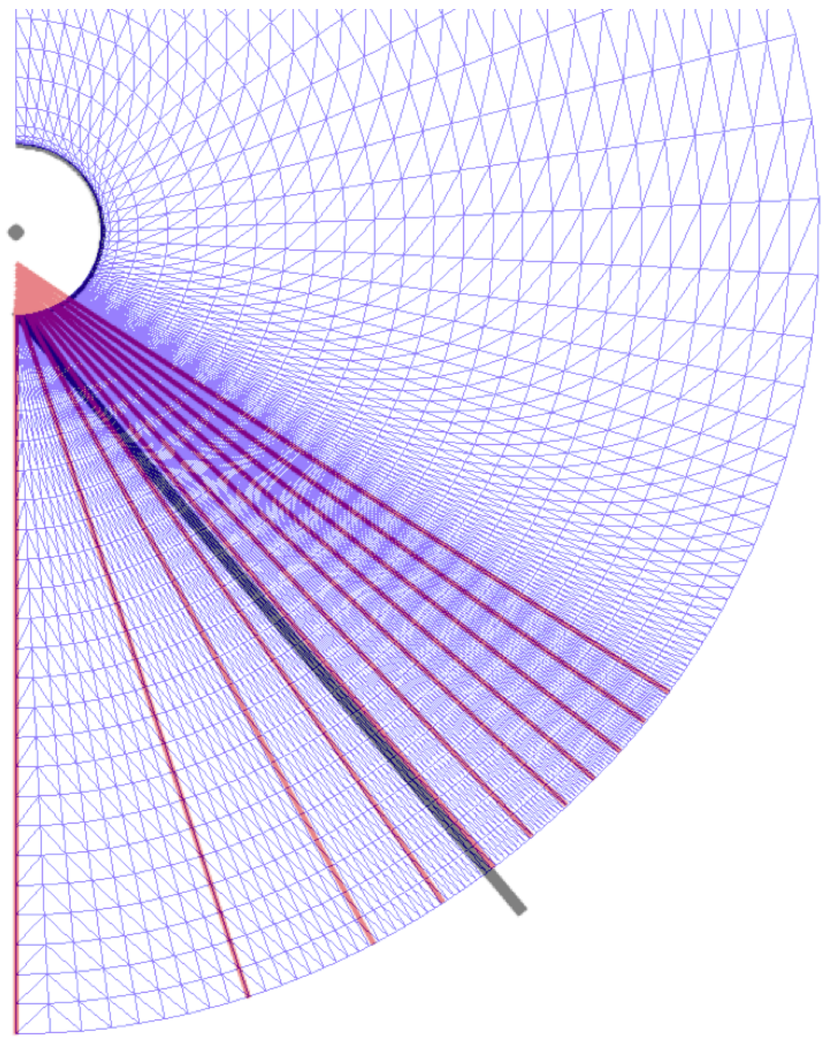
# Resulting Inflow Plane for the New Outer Grid



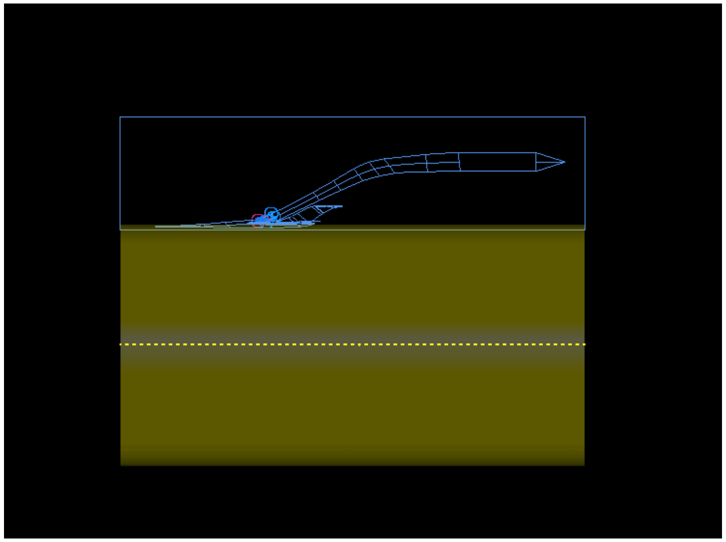
# Zpr Line Location for the Off-Track Signature Case



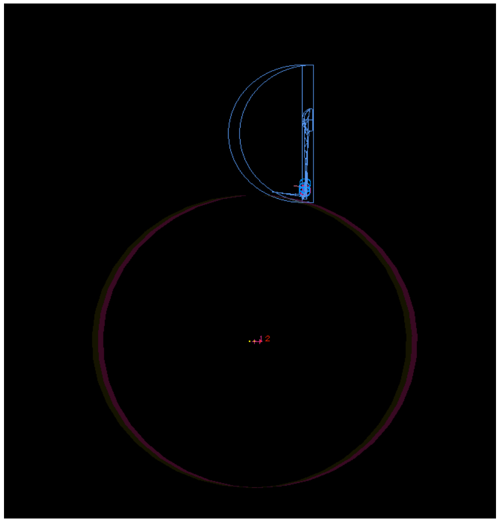
# Grid Clustering for the Desired Off-Track Angle



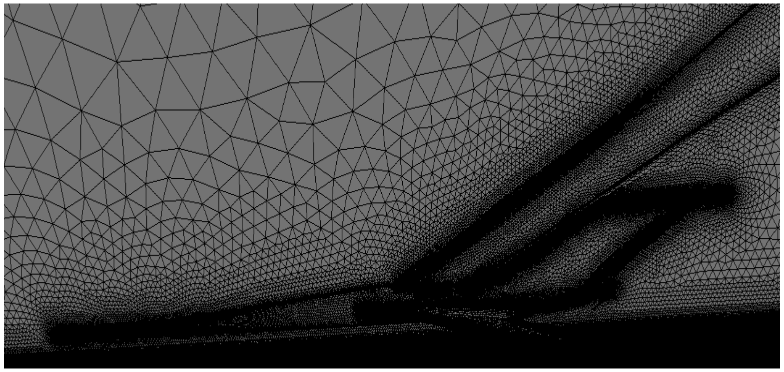
# Grid Generation for the BG Method – Gulfstream Configuration



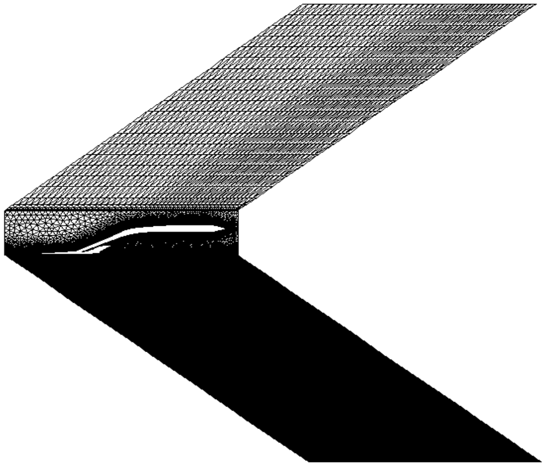
Side view



Rear view



Surface grid



Stretched grid

# Flow Solution Methodology

# Grid Generation Statistics

- Automatic sourcing using AUTOSRC code took less than a minute on Columbia supercomputer at the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center
- Surface and volume grid generation for the inner grids using VGRID was carried out locally on a Mac workstation. Depending upon the grid, it took anywhere from 30 minutes to two hours.
- Grid modification part of the process took from less than a minute using BG to about an hour using MCAP on Columbia at NAS

# USM3D Run Statistics

- The parallel version of the flow solver was run on Pleiades supercomputer at the NAS facility
- A flow solution on the Gulfstream configuration took about 1150 CPU hours when 96 processors were used for a typical grid size of 35 million cells
- On the Lockheed Martin configuration, a flow solution took about 1850 CPU hours when 96 processors were used for a typical grid size of 29.4 million cells
- On the SLSLE configuration, a flow solution took about 2900 CPU hours when 512 processors were used for a typical grid size of 68.8 million cells

# Flow Solver and Run Parameters

For the flow solutions, the following were used:

- USM3D flow solver for fully turbulent and laminar flow runs
- “Mixed Flow” version of USM3D flow solver for the mixed flow runs
- Shear Stress Transport (SST) turbulence model
- ‘minmod’ limiter
- $Y^+$ of 0.5

# Results

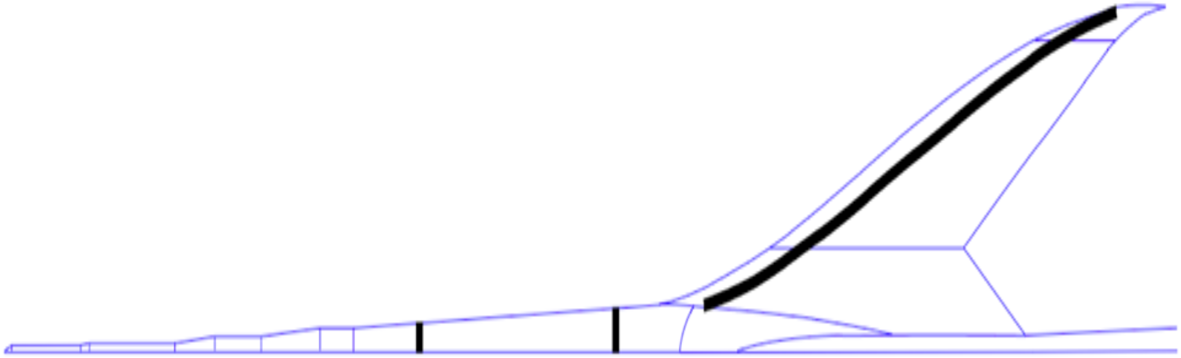
# Gulfstream Configuration

# Run Parameters

For all of the flow solutions on the Gulfstream configuration:

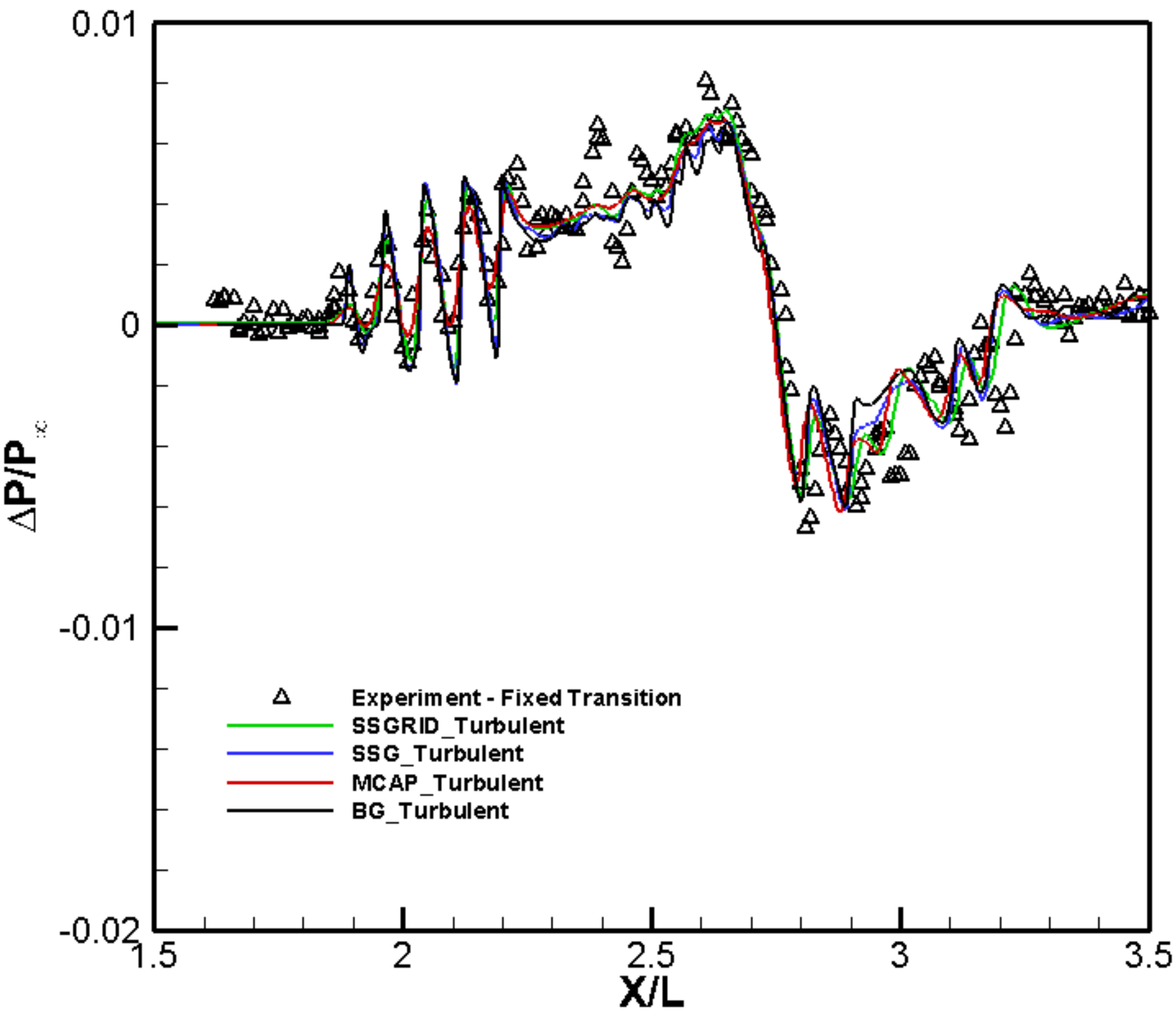
- Mach number = 1.56
- Angle of attack = 0.256 degrees
- Reynolds number = 3.86 million, based on reference length of 13.2 inches

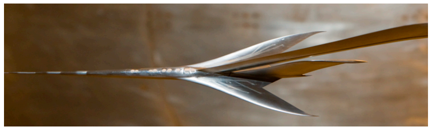
# Experimental Gulfstream Boom Model



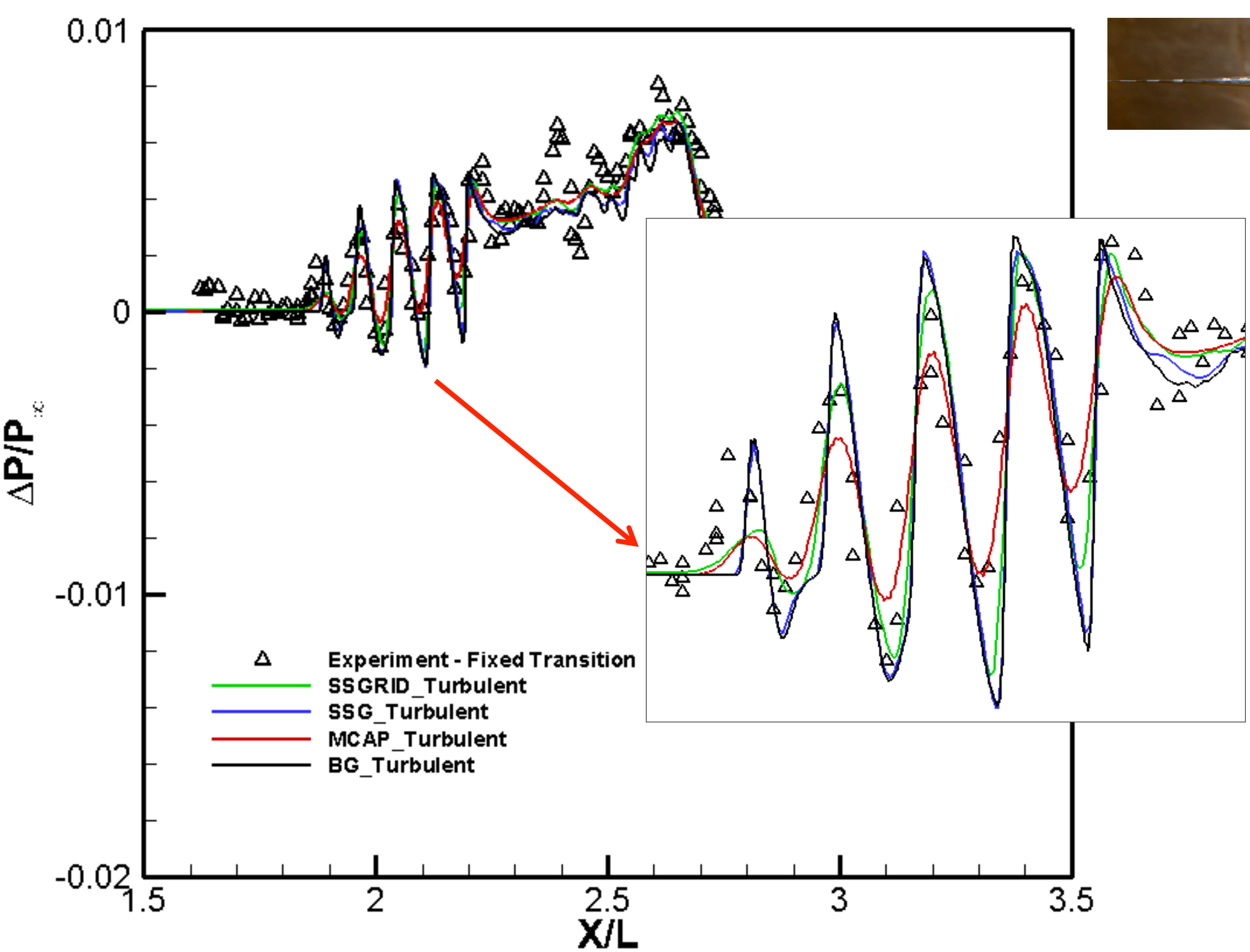
Schematic of trip locations on the model (denoted in black) – fixed transition run

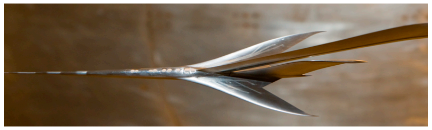
# On-Track Pressure Signatures of Grid Adaption Schemes (Φ=0, H/L=1.7)



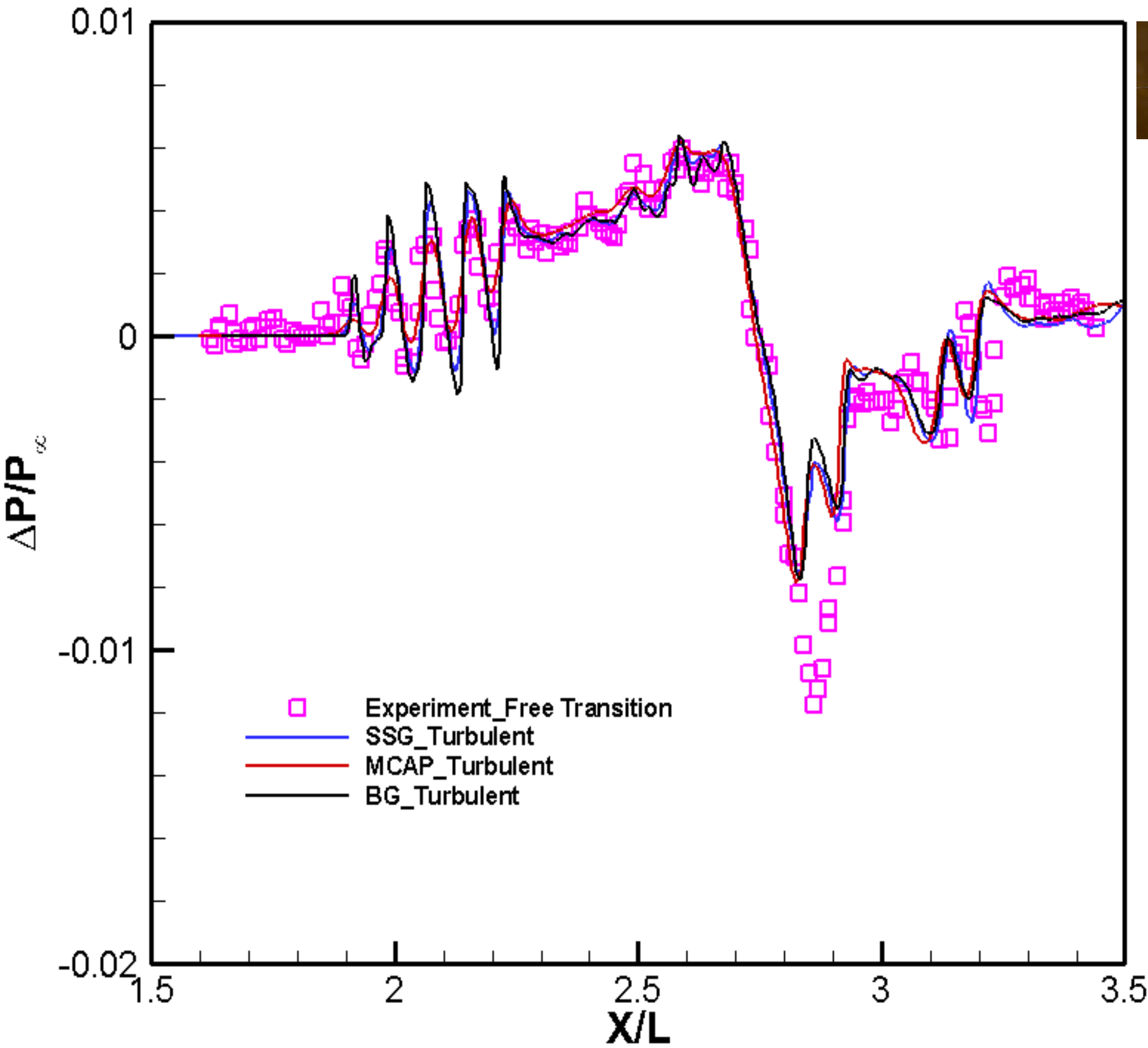



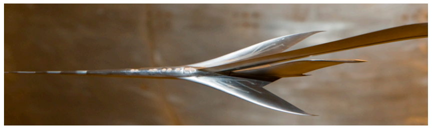
# On-Track Pressure Signatures of Grid Adaption Schemes (Φ=0, H/L=1.7)



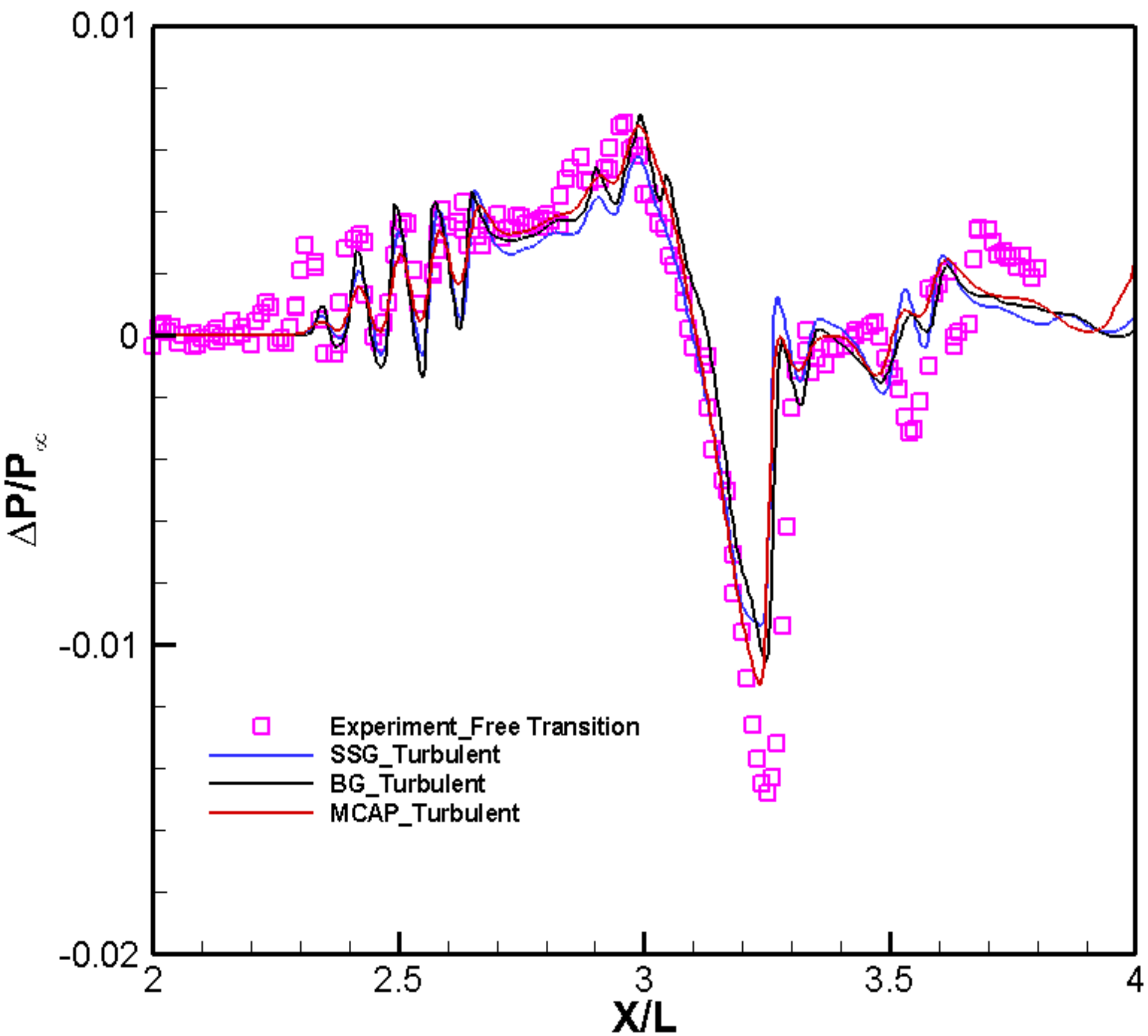



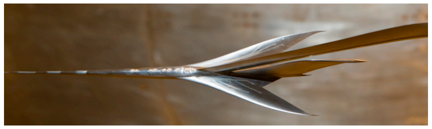
# Off-Track Pressure Signatures of Grid Adaption Schemes (Φ=25, H/L=1.73)



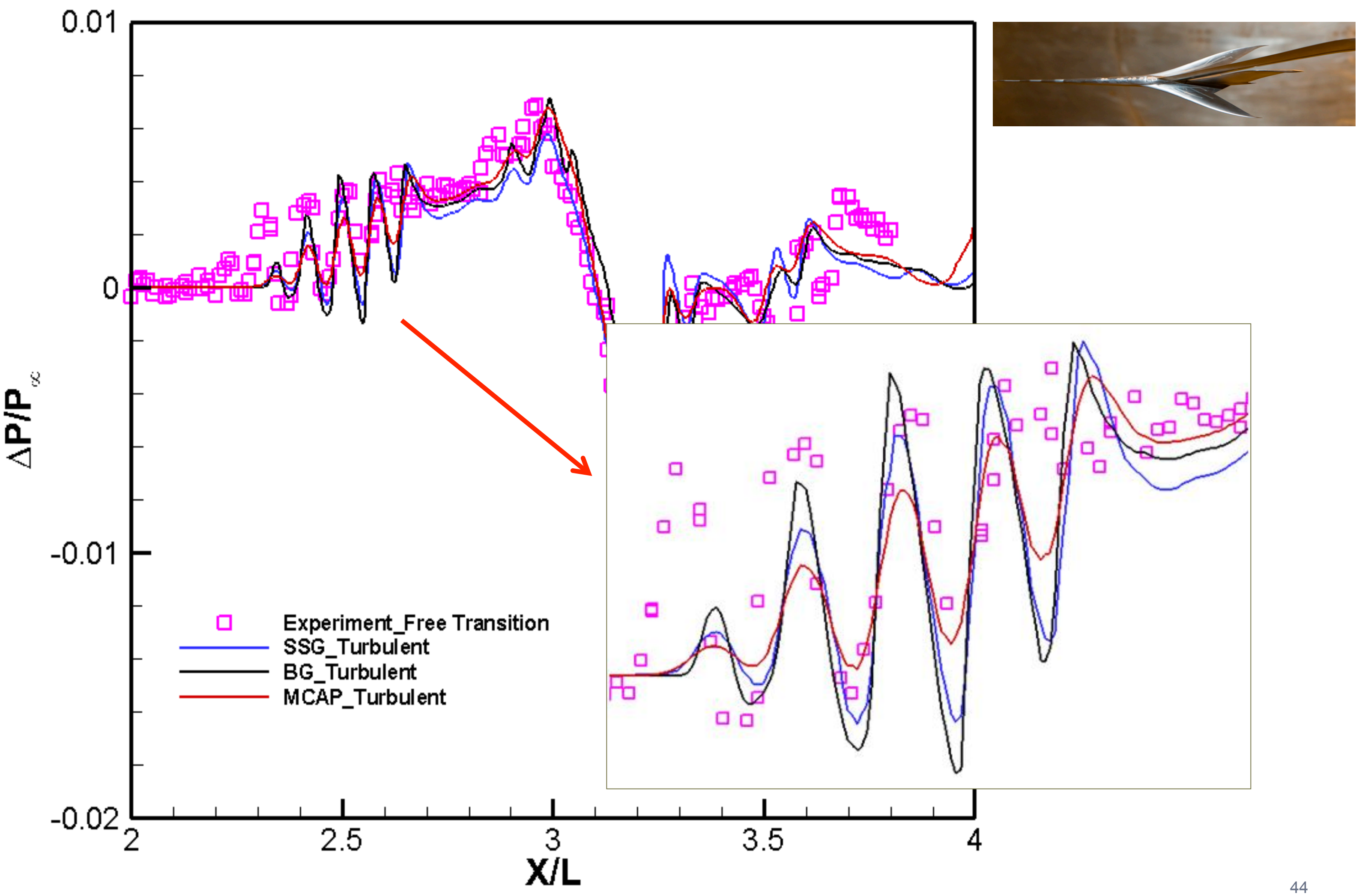



# Off-Track Pressure Signatures of Grid Adaption Schemes (Φ=53, H/L=1.829)

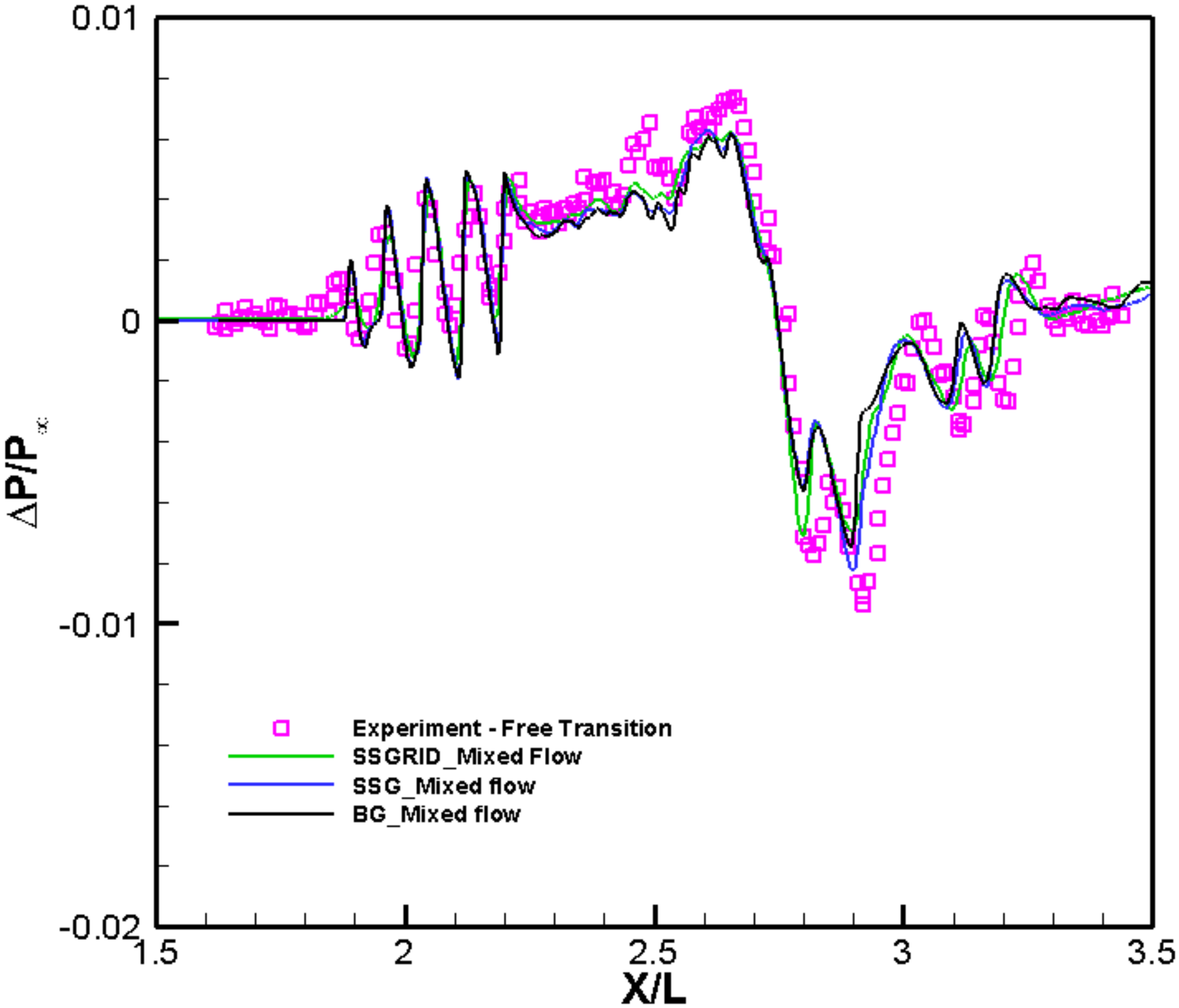


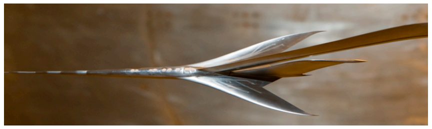



# Off-Track Pressure Signatures of Grid Adaption Schemes (Φ=53, H/L=1.829)

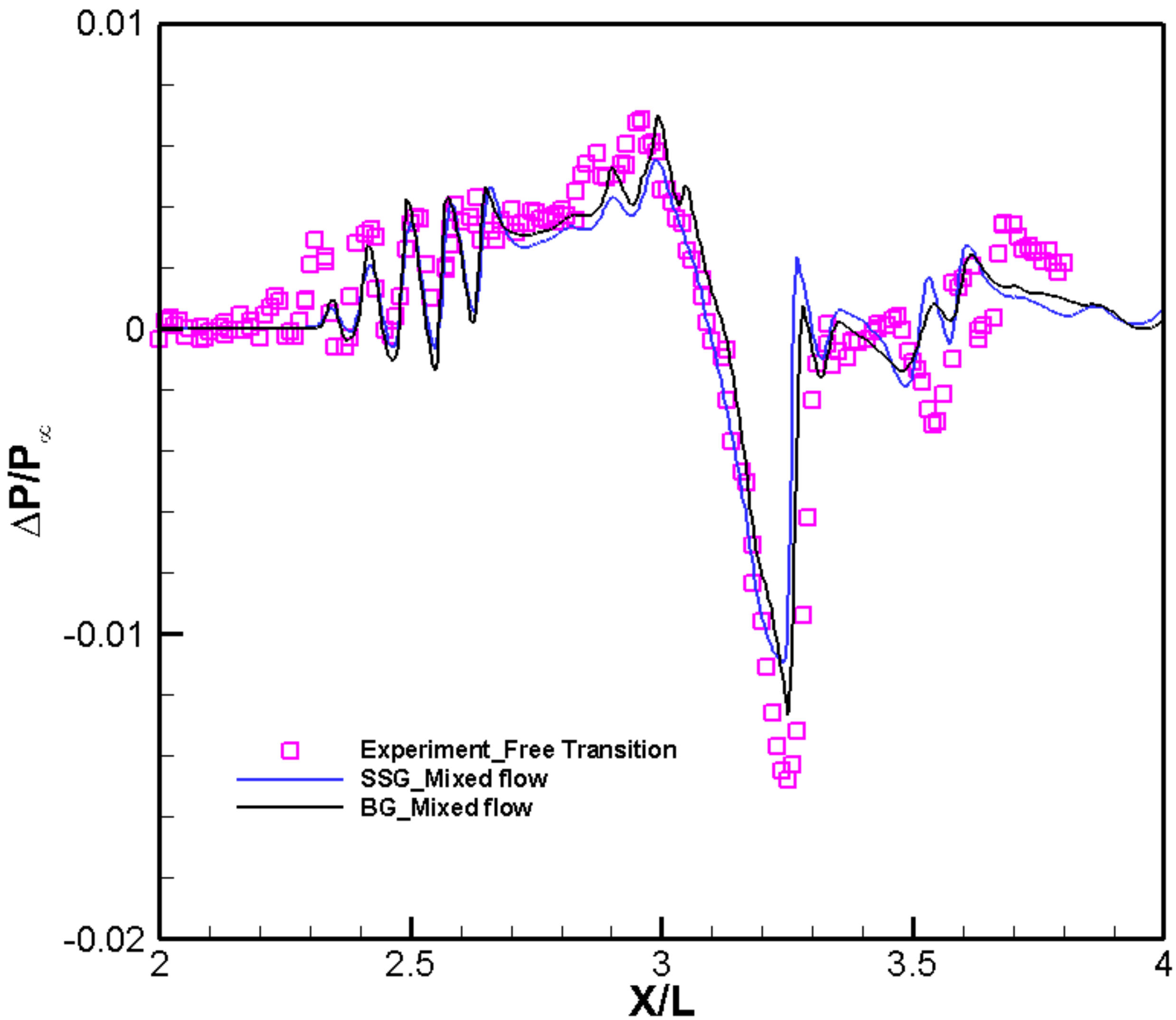


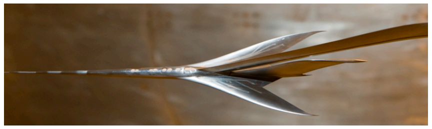
# On-Track Pressure Signatures of Grid Adaption Schemes (Mixed Flow, Wing Only Treated as Laminar, Φ=0, H/L=1.7)



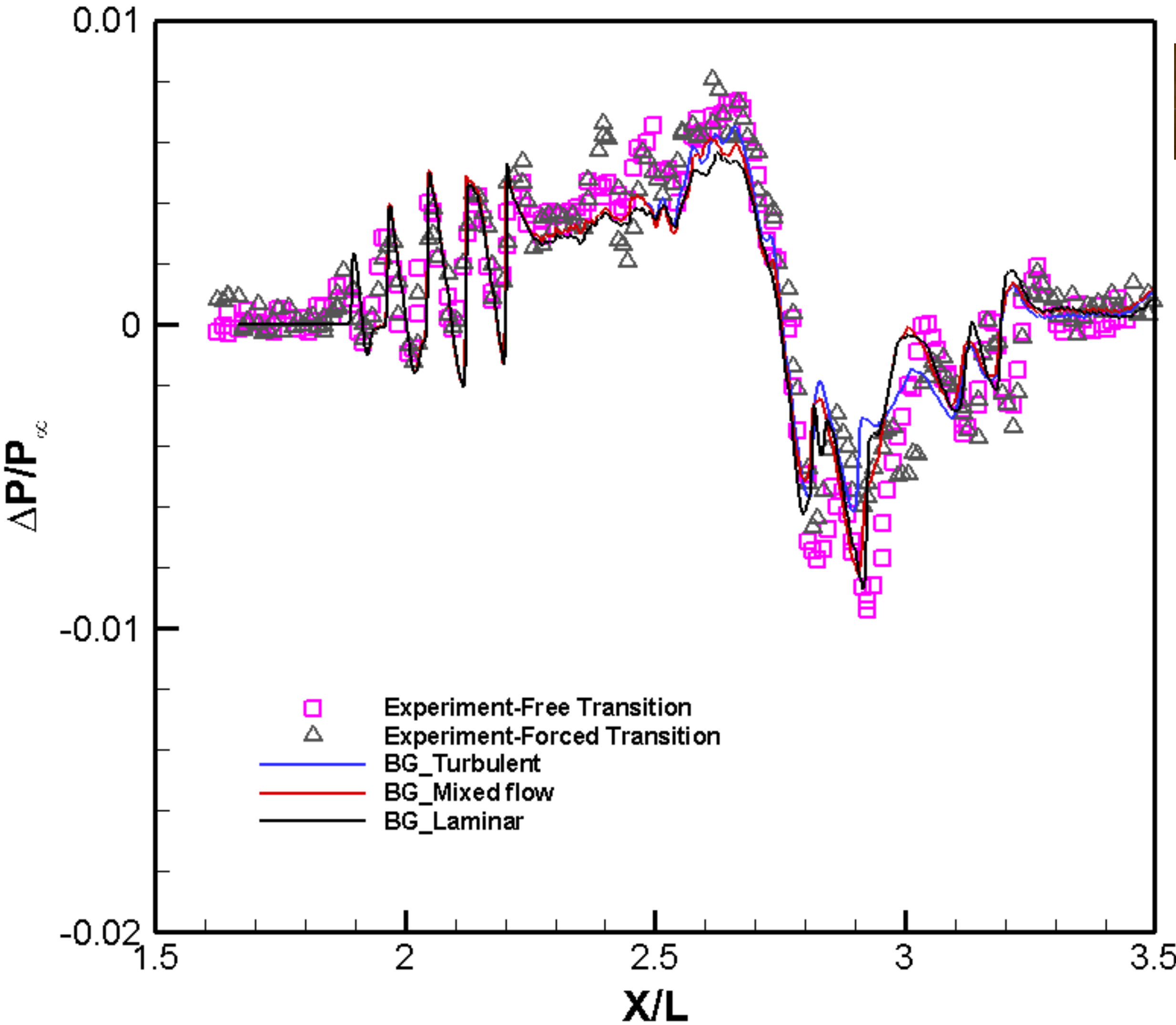



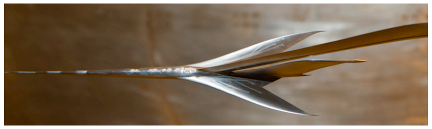
# Off-Track Pressure Signatures of Grid Adaption Schemes (Mixed Flow, Wing Only Treated as Laminar, Φ=53, H/L=1.829)



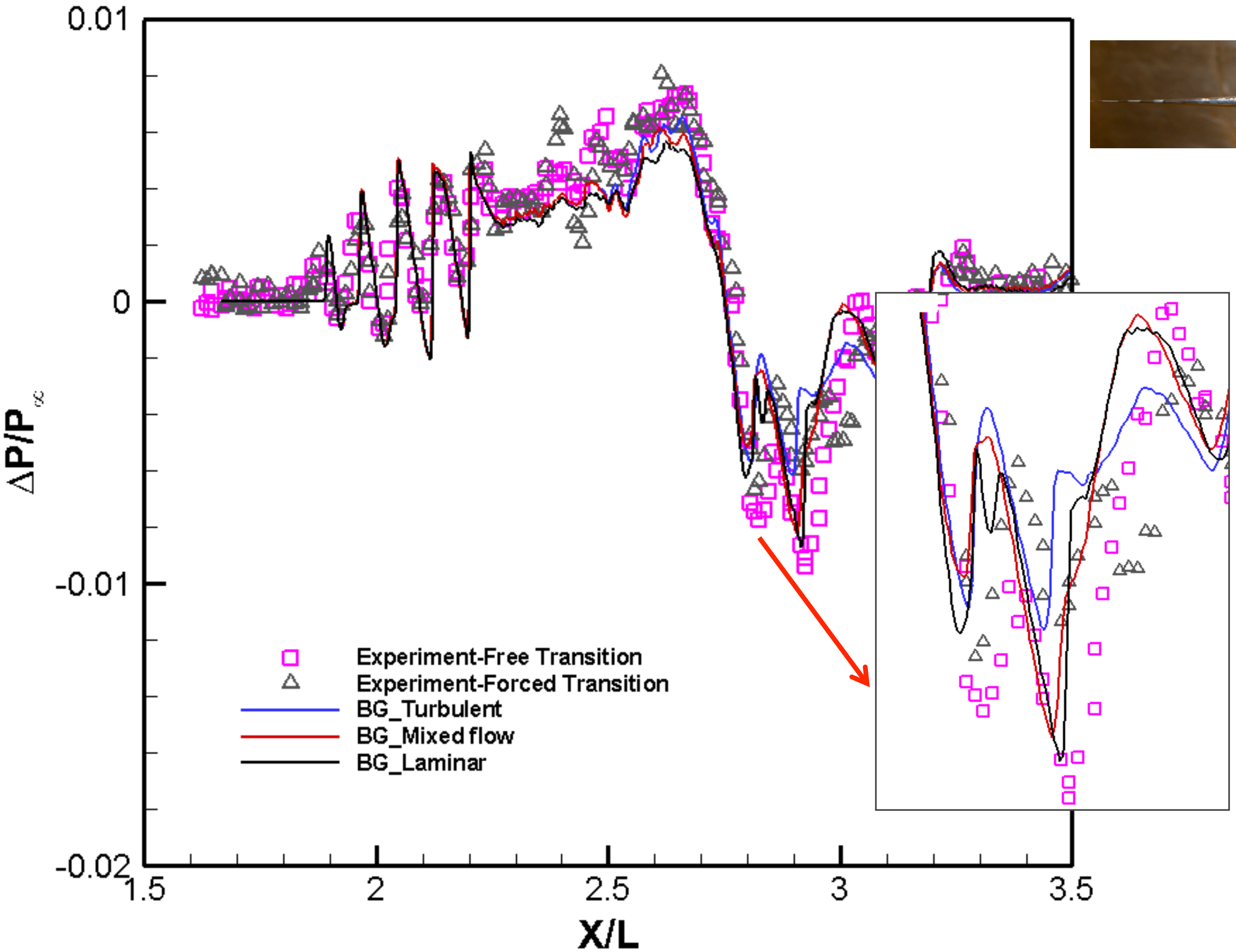



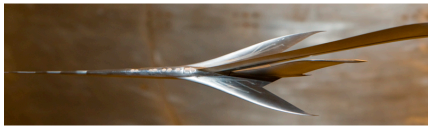
# On-Track Pressure Signatures of BG for Different Flow Conditions (Φ=0, H/L=1.7)



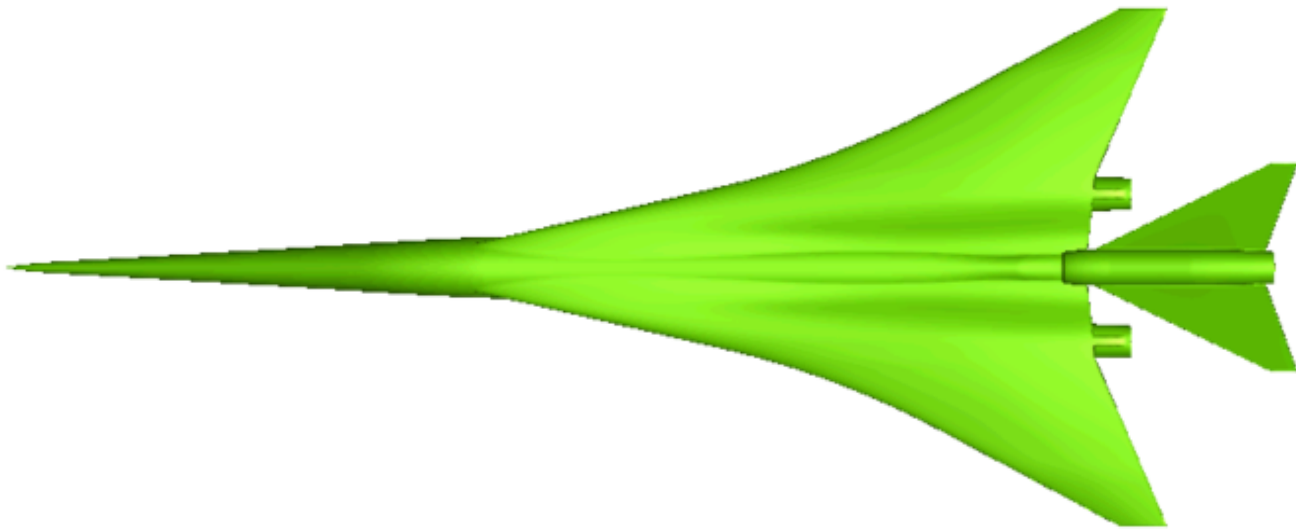



# On-Track Pressure Signatures of BG for Different Flow Conditions (Φ=0, H/L=1.7)



# Lockheed Martin Configuration



Reference 10, Cliff etc. al.

# Run Parameters

For all the flow solutions on the Lockheed configuration:

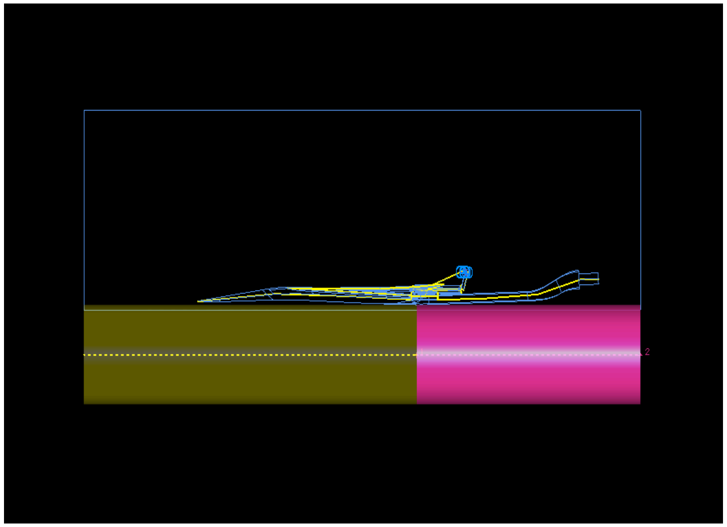
Mach number = 1.6

Angle of attack for on-track = 2.6 degrees

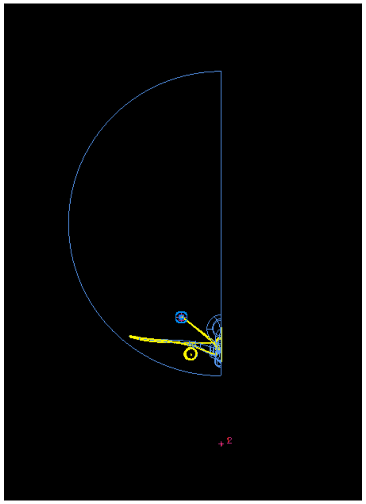
Angle of attack for 40 degrees off-track = 3.0 degrees

Reynolds number = 8.0 million, based on reference length of 22.365 inches

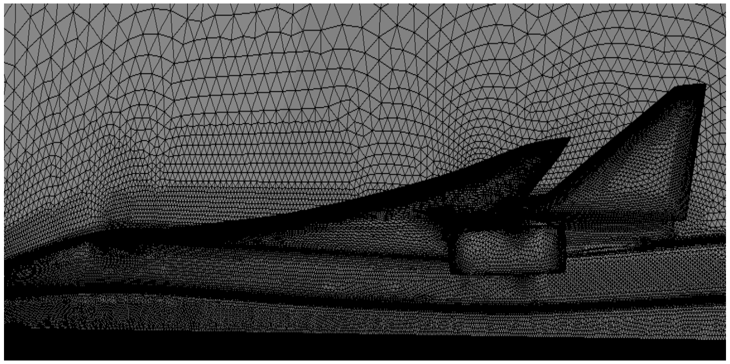
# Grid Generation for the BG Method – Lockheed Configuration



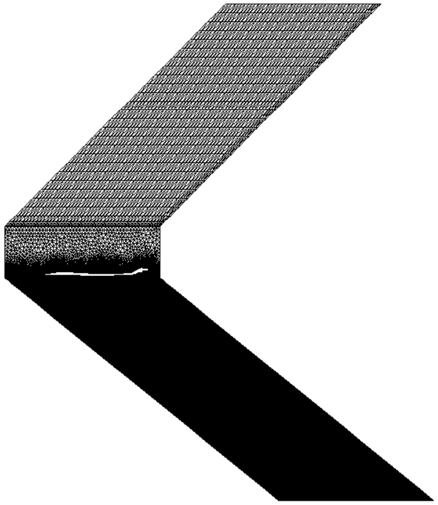
Side view



Rear view

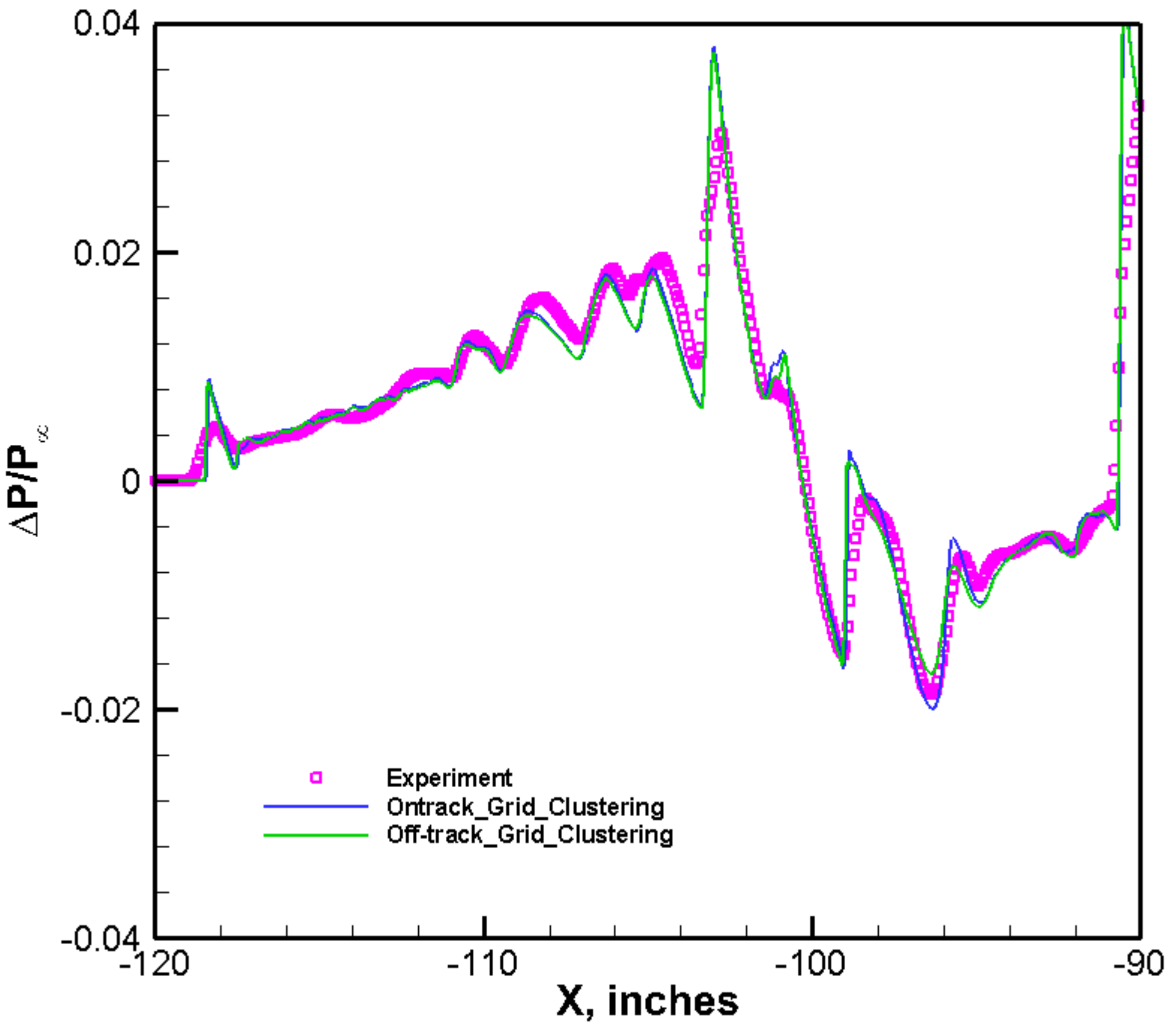


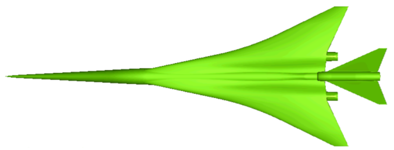
Surface grid



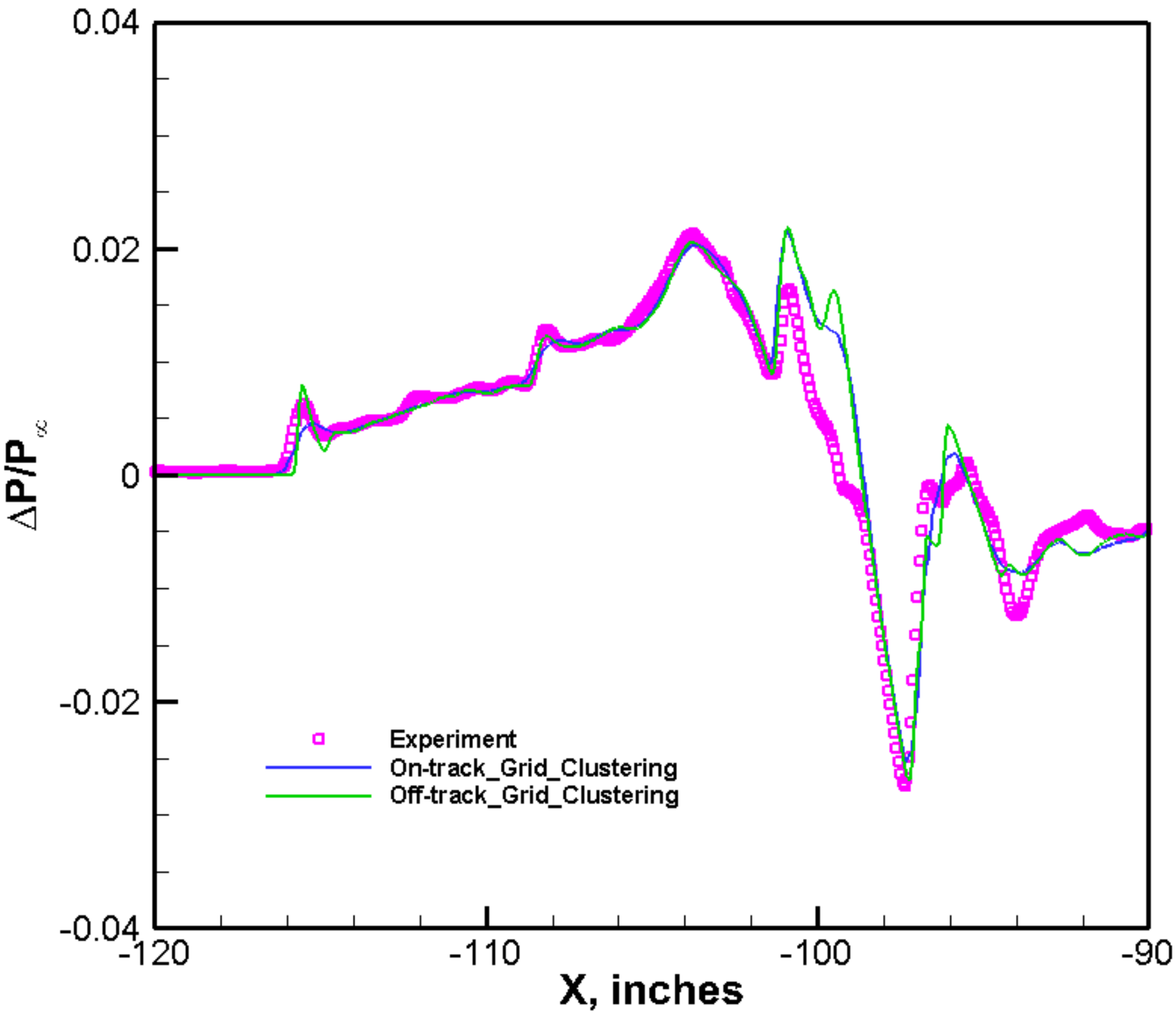
Stretched grid

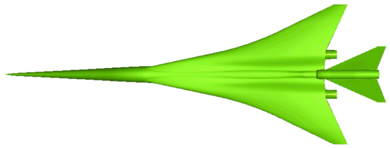
# Effects of On-Track and 40 Degrees Off-Track Grid Clustering (Signature at Φ=0, H/L = 0.94)



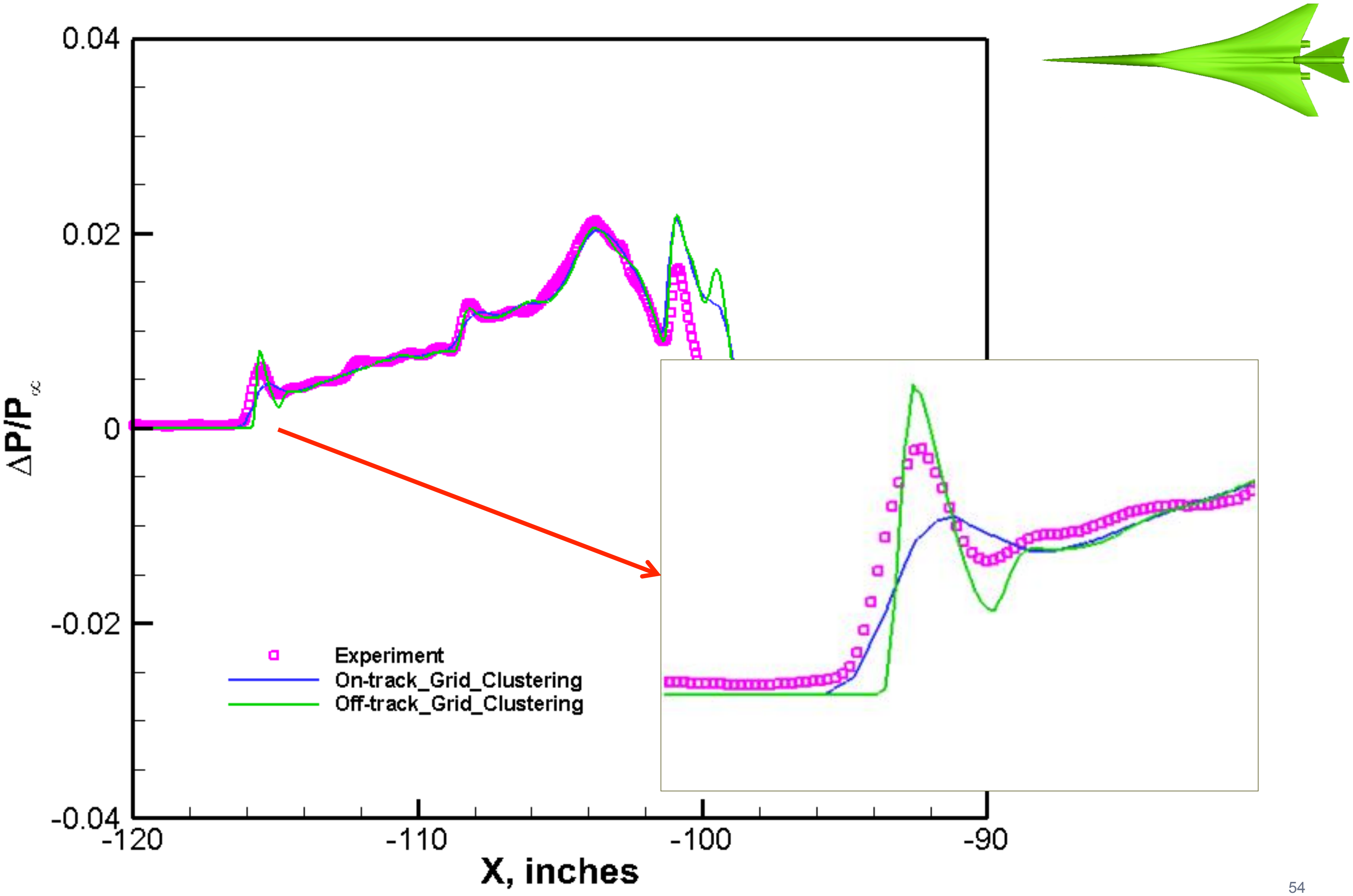



# Effects of On-Track and 40 Degrees Off-Track Grid Clustering (Signature at Φ=40, H/L = 0.94)

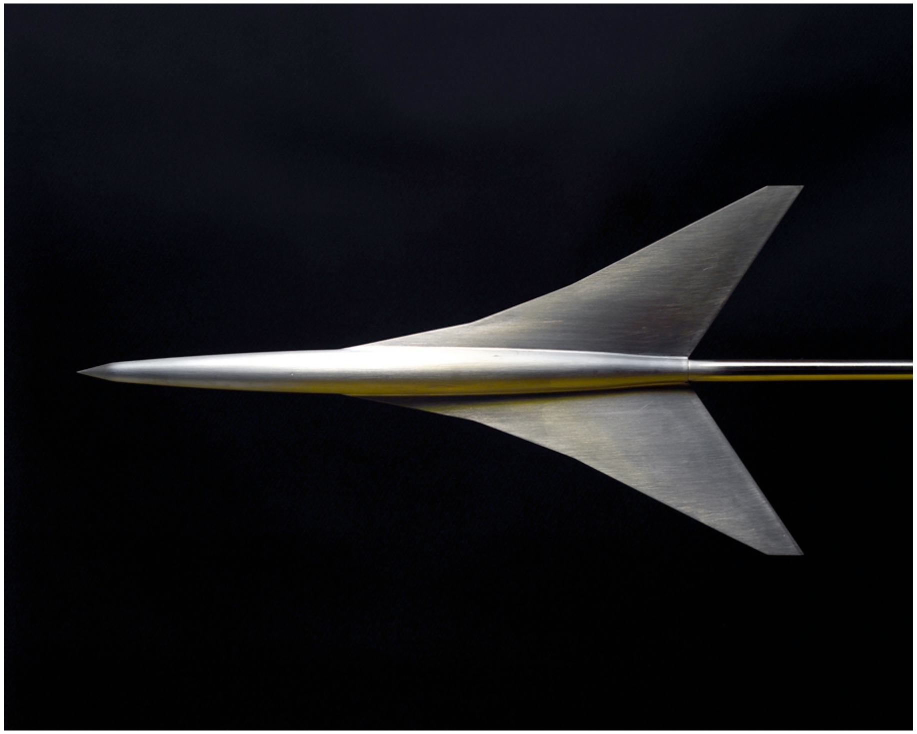


# Effects of On-Track and 40 Degrees Off-Track Grid Clustering (Signature at Φ=40, H/L = 0.94)



# Straight Line Segmented Leading Edge (SLSLE) Configuration



Reference 18, Elmiligui etc. al.

# Run Parameters

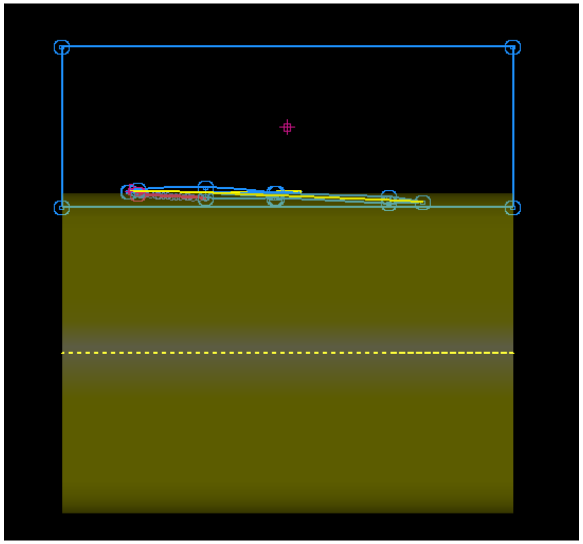
For all the flow solutions on the SLSLE configuration:

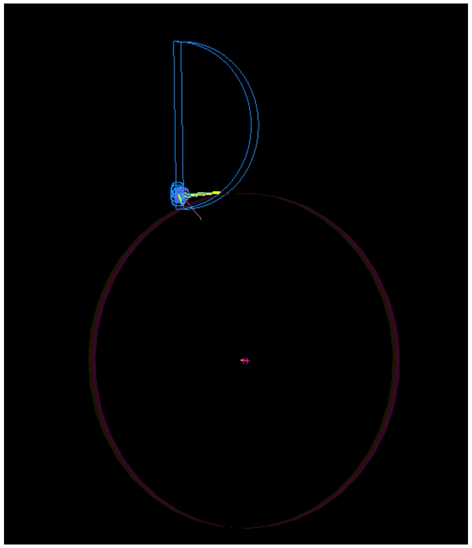
Mach number = 2.0

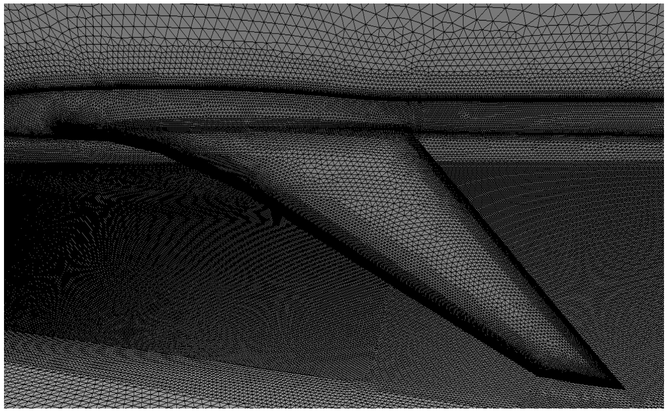
Angle of attack = 2.3 degrees

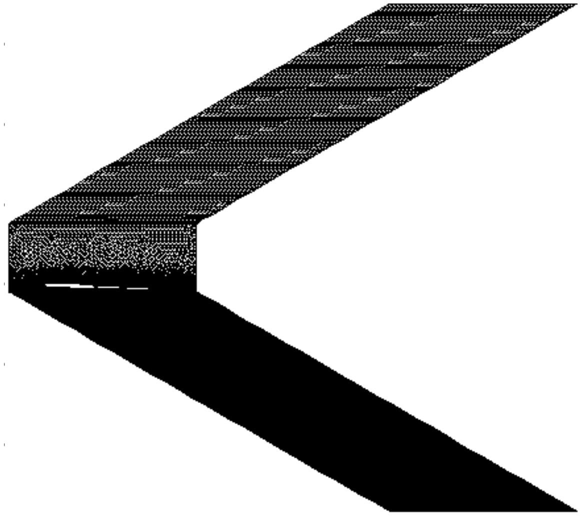
Reynolds number = 1.5 million, based on reference length of 9.0 inches

# Grid Generation for the BG Method – SLSLE Configuration


Side view


Rear view

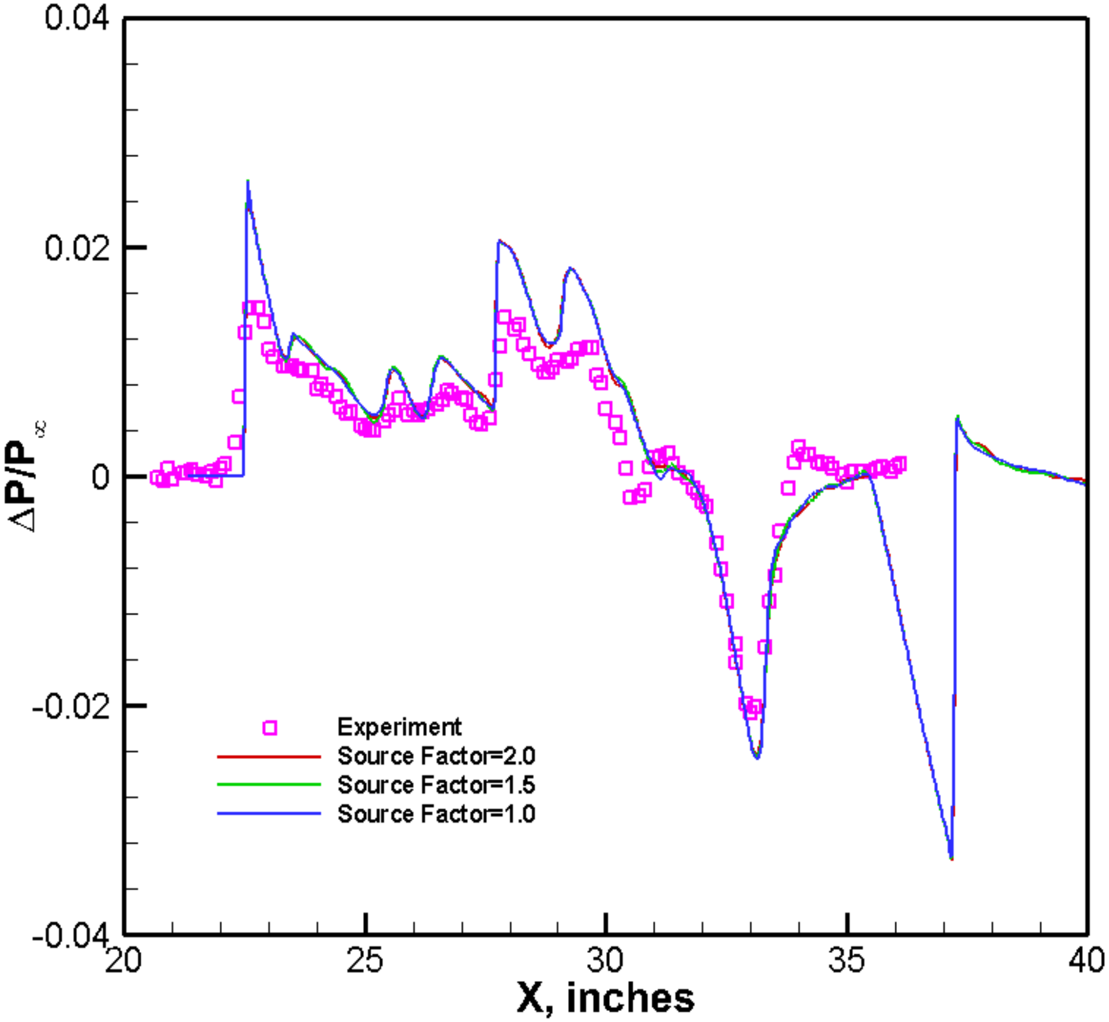

Surface grid

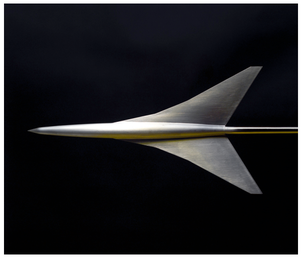

Stretched grid

# Grid Sensitivity Study

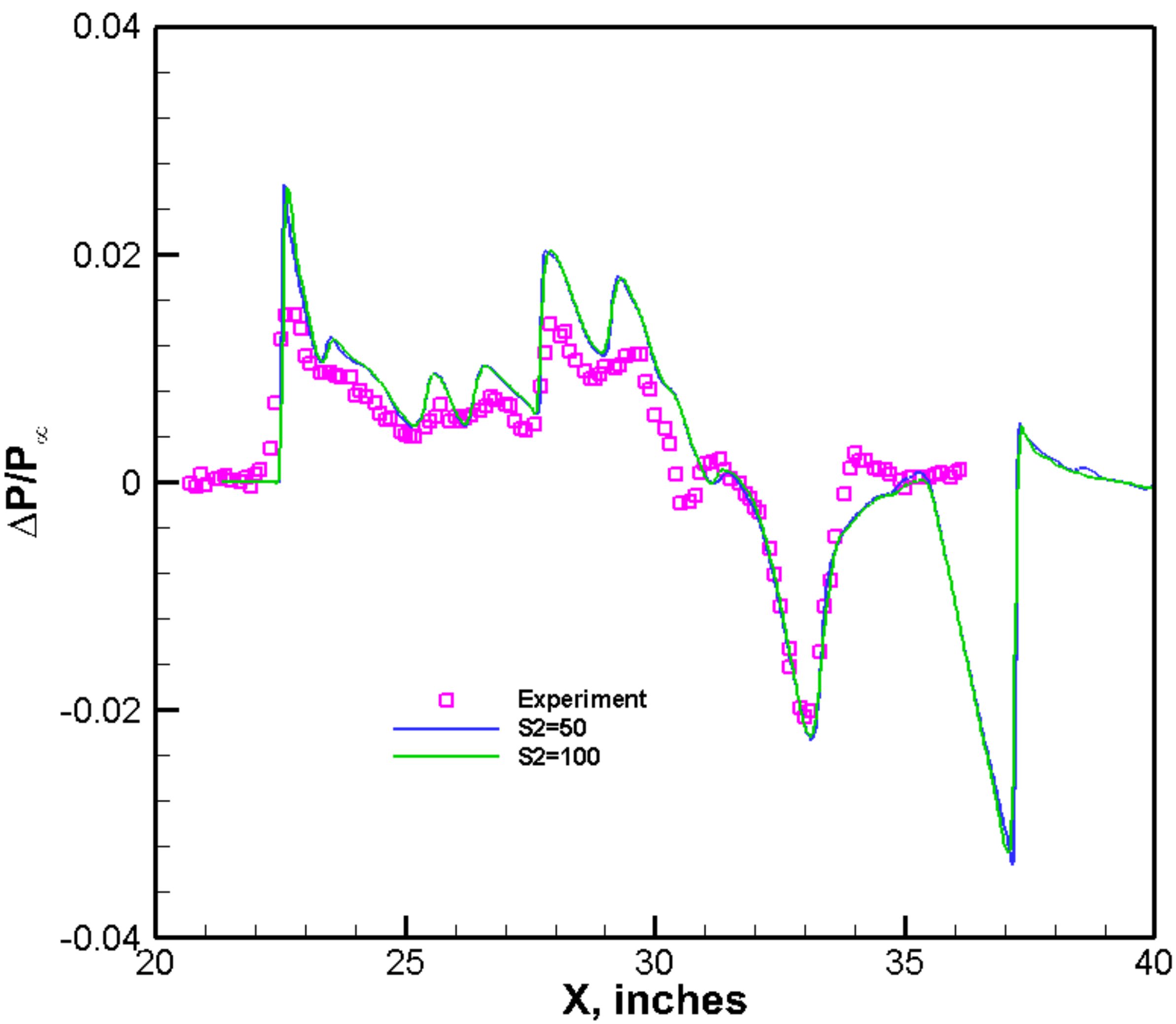
| Overall Source Factor in AUTOSRC | Inner Core Grid Size (number of cells) | Final Grid Size after Adding the Collar (number of cells) |
|---|---|---|
| 2.0 | 23,911,939 | 64,687,366 |
| 1.5 | 25,799,139 | 66,792,168 |
| 1.0 | 29,366,007 | 68,768,502 |

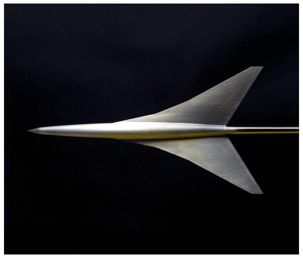
# On-Track Pressure Signature for Three Different Overall Source Factors (H/L = 1.5)



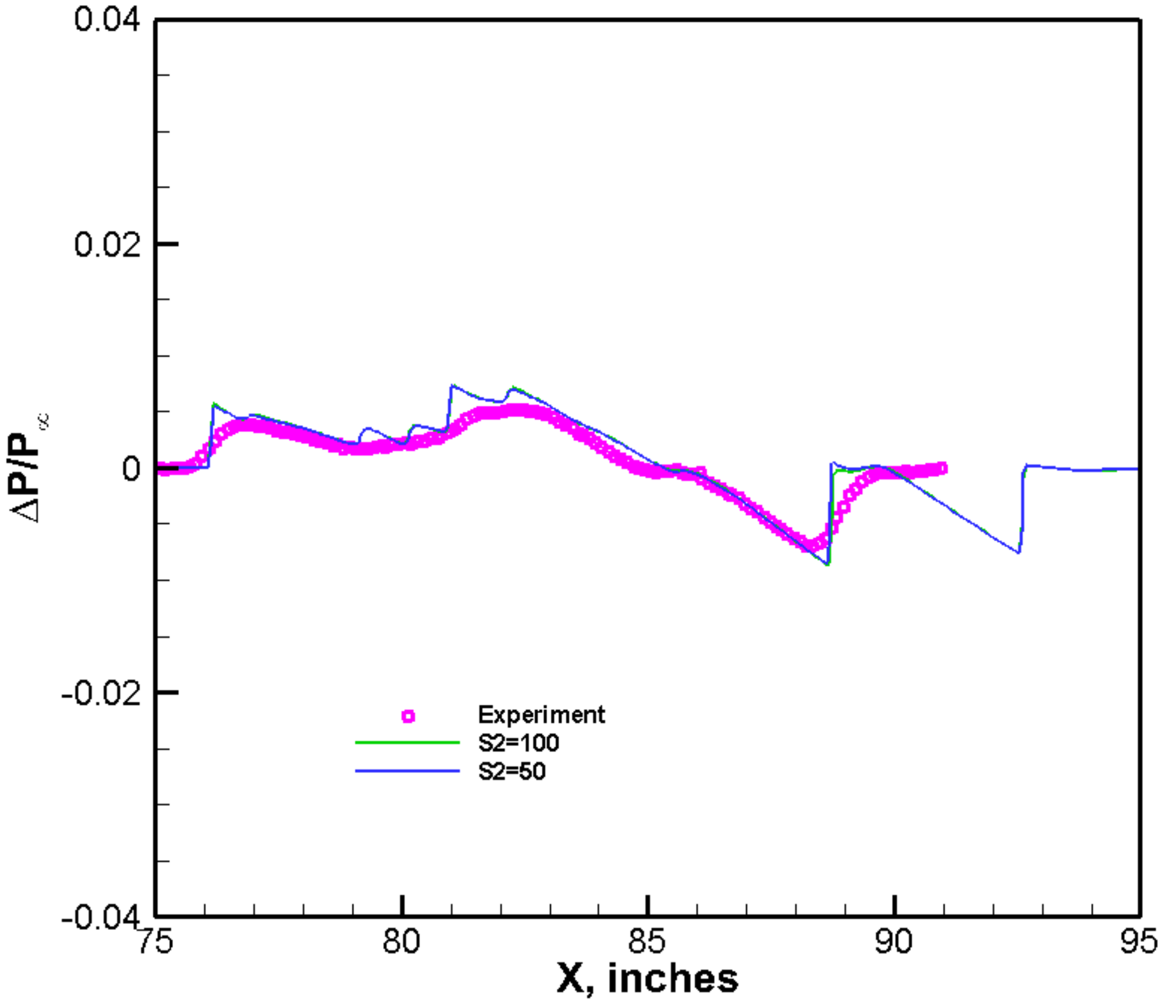



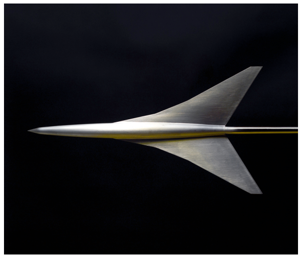
# On-Track Pressure Signature for Two Different Stretching Factors (H/L = 1.5)



# On-Track Pressure Signature for Two Different Stretching Factors (H/L = 10)



# Suggested Best Practices for BG

- Overall source factor of 2.0 in AUTOSRC
- Use a spacing factor (S2) of 100 in BG code
- For off-track angles of 40 degrees or less, a grid clustered at the off-track angle may also be used for on-track signatures with little loss in accuracy

# Concluding Remarks

- Two new grid modification codes, SSG and BG, have been developed for low boom analysis
- In general, all four methods evaluated gave good results when they ran (the BG method was the only one to successfully compute all of the test cases)
- The prism-extrusion methods (MCAP, BG) gave better flow solution convergence (though not necessarily more accurate boom signatures) than the grid stretching methods (SSGRID, SSG)
- BG was the only method evaluated with the capability to cluster the grid at a specified off-track angle
- BG typically required less time than the other grid stretching methods and was at least an order of magnitude faster than MCAP

# Acknowledgements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- The "mixed flow" version of the USM3D code was provided by Dr. Mohagna Pandya of NASA Langley Research Center